Volume 1

Climate Vulnerability

Understanding and Addressing Threats to Essential Resources

Volume 1: Vulnerability of Human Health to Climate

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CLIMATE VULNERABILITY

UNDERSTANDING AND ADDRESSING THREATS TO ESSENTIAL RESOURCES

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VOLUME 1

VULNERABILITY OF HUMAN HEALTH TO CLIMATE

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He has studied terrain-induced mesoscale systems, including the development of a three-dimensional mesoscale model of the sea breeze, for which he received the NOAA Distinguished Authorship Award for 1974. He has worked for NOAA's Experimental Meteorology Lab (1971—74), The University of Virginia (1974—81), and Colorado State University (1981—2006). He served as Colorado State Climatologist from 1999—2006. He was an adjunct faculty member in the Department of Civil and Environmental Engineering at Duke University in Durham, North Carolina (July 2003—06). He was a visiting professor in the Department of Atmospheric Sciences at the University of Arizona from October to December 2004.

He has served as chairman and member of the AMS Committee on Weather Forecasting and Analysis, and was the chief editor for the Monthly Weather Review for 5 years from 1981 to 1985. In 1977, he received the AMS Leroy Meisinger Award for 'fundamental contributions to mesoscale meteorology through numerical modeling of the sea breeze and interaction among the mountains, oceans, boundary layer, and the free atmosphere'. He received the 1984 Abell New Faculty Research and Graduate Program Award, and also received the 1987/1988 Abell Research Faculty Award. He was declared 'Researcher of the Year' by the Colorado State University Research Foundation in 1993. In 2000, he received the Engineering Dean's Council Award from Colorado State University.

He authored a book published by Academic Press entitled 'Mesoscale meteorological modeling' in 1984 with a 2nd edition in 2002, a book for Routledge Press entitled 'The Hurricane in 1990, a book (coauthored with W.R. Cotton) for Cambridge Press entitled 'Human impacts on weather and climate in 1995; 2nd ed., 2006, a book (coauthored with R.A. Pielke, Jr.) entitled 'Hurricanes: Their nature and impacts on society' published in 1997 by John Wiley and Sons, and was co-chief editor (with R.A. Pielke, Jr.) of a book entitled 'Storms' published by Routledge Press in 1999.

He was elected as a fellow of the AMS in 1982 and fellow of the American Geophysical Union in 2004. From 1993—96, he served as editor-in-chief of the US National Science Report to the IUGG (1991—94) for the American Geophysical Union. From January 1996 to December 2000, he served as co-chief editor of the *Journal of Atmospheric Science*. In 1998, he received NOAA's ERL Outstanding Scientific Paper (with Conrad Ziegler and Tsengdar Lee) for a modeling study of the convective dryline. He was designated a Pennsylvania State Centennial Fellow in 1996, and named the Pennsylvania State College of Earth and Mineral Sciences Alumni of the year for 1999 (with Bill Cotton). He is currently serving on the AGU Focus Group on Natural Hazards (August 2009—Present) and the AMS Committee on Planned and Inadvertent Weather Modification (October 2009—Present). He is among one of three faculties and one of four members listed by ISI Highly Cited in Geosciences at Colorado State University and the University of Colorado at Boulder, respectively.

He has published over 370 papers in peer-reviewed journals, 55 chapters in books, coedited 9 books, and made over 700 presentations during his career to date. The listing of papers can be viewed at the project website: http://cires.colorado.edu/science/groups/pielke/pubs/. He also launched a science weblog in 2005 to discuss weather and climate issues. This weblog was named one of the 50 most popular Scienceblogs by Nature Magazine on 5 July 2006 and is located at http://pielkeclimatesci.wordpress.com/.

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Dr Jimmy Adegoke is an award winning climate scientist whose research focuses on understanding the relationships between changing land surface processes and diverse indicators of environmental change. His recent work focuses on societal impacts of environmental change including air pollution studies in rapidly changing midlatitude urban areas and climate impacts on water resources in the Lake Chad Basin. He teaches at the University of Missouri-Kansas City (UMKC) where he served as chair of the Department of Geosciences from 2008–10. From August 2010 until very recently, he was Executive Director of the Council for Scientific and Industrial Research (CSIR) Natural Resources and Environment (NRE) Division, Pretoria, South Africa where he also served as the Director of the Applied Center for Climate and Earth Systems Science (ACCESS), a Center of Excellence (CoE) of the South Africa Department of Science and Technology (DST) Global Change Grand Challenge (GCGC) program. He is a member of several professional societies including the American Geophysical Union (AGU), Association of American Geographers (AAG), and American Meteorological Society (AMS). He is on the advisory council of the African Association for Remote Sensing of the Environment (AARSE) and also serves on the technical advisory committee of several United Nations applied science programs, including the United Nations Educational Scientific and Cultural Organization (UNESCO) crosscutting project on the application of remote sensing for water resources and ecosystem management in Africa. He lives in Kansas city where he served a 3-year team as an appointee of the Mayor of Kansas City Missouri (KCMO) on the city's Environmental Management Commission (EMC).

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Dr Dev Niyogi is an associate professor with joint appointment in the Departments of Agronomy and Earth, Atmospheric, and Planetary Science at Perdue University.

He is also the State Climatologist for Indiana and Director of the Indiana State Climate Office. His research seeks to advance the understanding of vegetation and land surface processes in environmental, weather forecasting, and climate analyses, using a combination of dynamical models and surface, satellite remote sensing, and multiscale analysis products.

His research deals with the understanding and representation of the effects of vegetation – land surface processes in environmental processes at different scales. He is one of the three invited, nonfederal representatives to the community modeling effort of the Weather Research and Forecast (WRF) model working group on Land Surface Models, and to the Federal Geophysical Data Commission (FGDC) Spatial Climate Working Group.

He has authored or coauthored 25 successful proposals for external grants totaling over $3M. He vertically integrates undergraduate, graduate, and postdoctoral researchers in his research and is very interdisciplinary in developing collaborative projects.

Dr George Kallos is a professor at the University of Athens, School of Physics, Division of Environmental Physics and Meteorology. He leads the Atmospheric Modeling and Weather Forecasting Group (AM & WFG). He has a BSc from the University of Athens/School of Mathematics (1975). He obtained his MSc (1983) and PhD (1985) in Geophysical Sciences/ Atmospheric Sciences Division, Georgia Institute of Technology, School of Geophysical Sciences, USA. He has 110 publications in peer review scientific journals, more than 230 presentations and publications in conference proceedings publications, 10 contributions in books and more than 200 other publications in subjects related to atmospheric physics and chemistry, sea-state conditions, and renewable energy production. He has been invited 70 times to give talks in conferences, seminars, etc. His published work has received >2000 citations. He has participated in 80 projects. He has organized 12 conferences related to air pollution and dust transport in the Mediterranean. He has supervised 10 PhDs and over 100 MSc theses and participated in 20 PhD examinations in Greece and Europe. He is an associate editor for the journals: '*Environmental Fluid Mechanics*', '*Advances in Meteorology*', '*International Journal of Geosciences*', '*Atmospheric Pollution Research*', and '*Journal of Aerospace Operations*'. He was awarded the International Union of Air Pollution Prevention Association – IUAPPA award for his work on 'Long-range transport and air quality work in the Mediterranean region'. His current research activities are related to atmospheric, climatic, air pollution, and sea-state model development and forecasting. He focuses in fully coupled modeling systems. The latest model developments are related to nucleation processes in clouds, desert dust cycle and its direct and indirect effects. Research activities related to renewable energy resources (wind, ocean, solar) are focusing on high accuracy atmospheric model development, energy relationships and predictions, and protection from extremes.

Timothy Seastedt received his BA in biology from the University of Montana, an MS degree in biological sciences from the University of Alaska at Fairbanks, and a PhD degree from the University of Georgia. He was on the faculty at Kansas State University and is currently a professor of Ecology and Evolutionary Biology and fellow of INSTAAR at the University of Colorado, Boulder. Much of his research has been conducted as part of the Long-Term Ecological Research (LTER) programs at KSU and CU. His interests focus on terrestrial ecosystem ecology and the causes and consequences of biotic change. His recent activities have emphasized the ongoing changes found along the grassland to (melting) glacier gradient that exists in the Colorado Front Range.

Katharine Suding received her BA in biology from Williams College and a PhD degree from the University of Michigan. She was on the faculty at University of California Irvine and is currently a professor in Environmental Science, Policy and Management at the University of California Berkeley. Her background is in plant community and ecosystem ecology, with current interests in restoration, resilience, and environmental change.

Faisal Hossain received his PhD from the University of Connecticut in 2004. Prior to that, he had earned his MS and BS from the National University of Singapore and Indian Institute of Technology, Varanasi, respectively. He is currently an associate professor in the Department of Civil and Environmental Engineering where he received one of the highest awards of University – the Caplenor Research Award in 2012. His research interests comprise hydrologic remote sensing, uncertainty modeling of water cycle variables, human modification of extreme hydro-climatology, sustainable water resources engineering, space-borne transboundary water resources management, engineering education, and public outreach. He is also the recipient of awards such as NASA Earth System Science Fellowship (2002), Outstanding PhD Thesis Award (2005), NASA New Investigator Award (2008), American Society of Engineering Education (ASEE) Outstanding Research Award (2009), National Association of Environmental Professionals Education Excellence Award (2010), US Fulbright Faculty Award (2012), G.O.L.D. (Graduate Of the Last Decade) award from University of Connecticut (2012), and American Geophysical Union (AGU) Charles Falkenberg Award. He has published over 85 peer-reviewed journal articles, authored an undergraduate-level textbook, edited two book volumes, and contributed eight book chapters. His recent research on human modification of extreme events by artificial reservoirs has been featured by public media such as the BBC, National Geographic, New Scientist, Newsweek, Fox News, MSNBC, Wired.com, and German Public Radio. He served as an associate editor of *Journal of American Water Resources Association* from 2006–10. Currently, he serves as an associate editor for *Journal of Hydrometeorology* and a lead editor for the water volume of Elsevier Sciences five volume reference series on '*Climate Vulnerability: Understanding and Addressing Threats to Essential Resources*'.

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PREFACE

We are pleased to introduce the five-volume set of books on bottom-up, resource-based vulnerability assessments of the societally and environmentally key resources of water, food, energy, human health and well-being, and ecosystem function. This inclusive bottom-up vulnerability concept requires the determination of the major threats to these resources from climate, but also from other social and environmental issues. After these threats are identified for each resource, the relative risk from natural- and human-caused climate change (estimated from global climate model (GCM) projections, as well as the historical, paleorecord, and worst case sequences of events) can be compared with other environmental and social risks in order to adopt the optimal mitigation and adaptation strategies.

The bottom-up, resource-based approach (referred to by O'Brien (2009) as ‘contextual vulnerability’) that is the focus of the volume is distinct from the Intergovernmental Panel on Climate Change (IPCC) top-down assessment of vulnerability based on the multidecadal GCM predictions (projections) which O'Brien defined as ‘outcome vulnerability’ (**Table 1** and **Figure 1**).

An excellent example of the contextual vulnerability is the paper by Romero-Lankao et al. (2012) who concluded in a study of the literature that urban vulnerability is dominated by epidemiological studies and top-down assessments, but that inherent urban vulnerability and urban resilience approaches (the contextual vulnerability) are what is required in order to illuminate a more complete set of drivers of urban vulnerability. They also showed that the large majority of papers on vulnerability use the outcome vulnerability approach. However, as discussed below, this top-down approach has major flaws.

First, there is the issue that the term ‘climate’ has two definitions. The broader view (and the one adopted by NRC (2005)) is that climate consists of the atmosphere, oceans, land, and cryosphere. This is the preferred usage. The second definition is that climate is the term used for the long-term (e.g., multidecadal) statistics of weather.

As reported in the NRC (2005) report and written in the Pielke et al. (2009) article with respect to human climate forcings.

> In addition to greenhouse gas emissions, other first-order human climate forcings are important to understanding the future behavior of Earth's climate. These forcings are spatially heterogeneous and include the effect of aerosols on clouds and associated precipitation [e.g., Rosenfeld et al. 2008], the influence of aerosol deposition (e.g., black carbon (soot) [Flanner et al. 2007] and reactive nitrogen [Galloway et al. 2004]), and the role of changes in land use/land cover [e.g., Takata et al. 2009]. Among their effects is their role in altering atmospheric and ocean circulation features away from what they would be in the natural climate system [NRC 2005]. As with CO_2, the lengths of time that they affect the climate are estimated to be on multidecadal timescales and longer.

and

> “…the natural causes of climate variations and changes are important, as are the human influences. The human climate forcings involve a diverse range of first-order climate forcings, including, but not limited to, the human input of carbon dioxide (CO2). Most, if not all, of these human influences on regional and global climate will continue to be of concern during the coming decades.”

Threats from climate involve any one or combination of climate variables as illustrated in **Figure 2**. There do not, of course, have to be changes in the statistics of these variables to constitute a risk. The term

Table 1 Contrast between a top-down versus bottom-up assessment of the vulnerability of resources to climate variability and change

Approach	*Comparative vulnerability*	*Contextual vulnerability*
Assumed dominant stress	Climate, recent greenhouse gas emissions to the atmosphere, ocean temperatures, aerosols, etc.	Multiple stresses: climate (historical climate variability, land use and water use, altered disturbance regimes, invasive species, contaminants/pollutants, habitat loss, etc.)
Usual timeframe of concern	Long-term, doubled CO_2 30—100 years in the future.	Short-term (0—30 years) and long-term research.
Usual scale of concern	Global, sometimes regional. Local scale needs downscaling techniques. However, there is little evidence to suggest that present models provide realistic, accurate, or precise climate scenarios at local or regional scales.	Local, regional, national, and global scales.
Major parameters of concern	Spatially averaged changes in mean temperatures and precipitation in fairly large grid cells with some regional scenarios for drought.	Potential extreme values in multiple parameters (temperature, precipitations, frost-free days) and additional focus on extreme events (floods, fires, droughts, etc.) measures of uncertainty.
Major limitations for developing coping strategies	Focus on single stress limits preparedness for other stresses. Results often show gradual ramping of climate change-limiting preparedness for extreme events. Results represent only a limited subset of all likely future outcomes — usually unidirectional trends. Results are accepted by many scientists, the media, and the public as actual 'predictions'. Lost in the translation of results is that all models of the distant future have unstated (presently unknowable) levels of certainty or probability.	Approach requires detailed data on multiple stresses and their interactions at local, regional, national, and global scales, and many areas lack adequate information. Emphasis on short-term issues may limit preparedness for abrupt "threshold" changes in climate sometime in the short or long term. Requires preparedness for a far greater variation of possible futures, including abrupt changes in any direction — this is probably more realistic, yet difficult.

Adapted from Kabat et al. 2004.

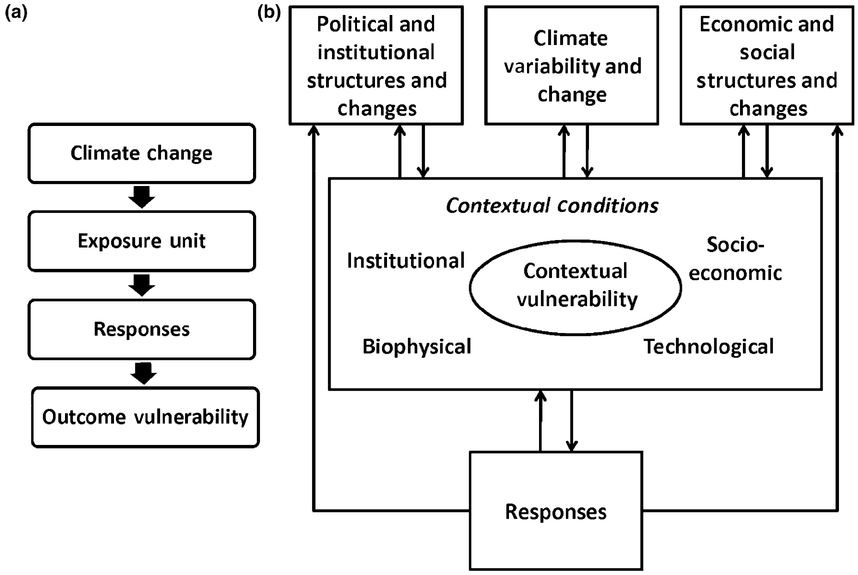
(a)
Climate change
Exposure unit
Responses
Outcome vulnerability
(b)
Political and institutional structures and changes
Climate variability and change
Economic and social structures and changes
Contextual conditions
Institutional
Contextual vulnerability
Socio-economic
Biophysical
Technological
Responses

Figure 1 Framework depicting two interpretations of vulnerability to climate change: (a) outcome vulnerability and (b) contextual vulnerability. *From: Füssel (2009) and O'Brien et al. (2007).*

'climate change' should be used to describe any multidecadal or longer alteration in one or more physical, chemical, and/or biological components of the climate system, but as explained below, this terminology has morphed into multiple, diverse (and often mutually exclusive) definitions as used by the impacts communities.

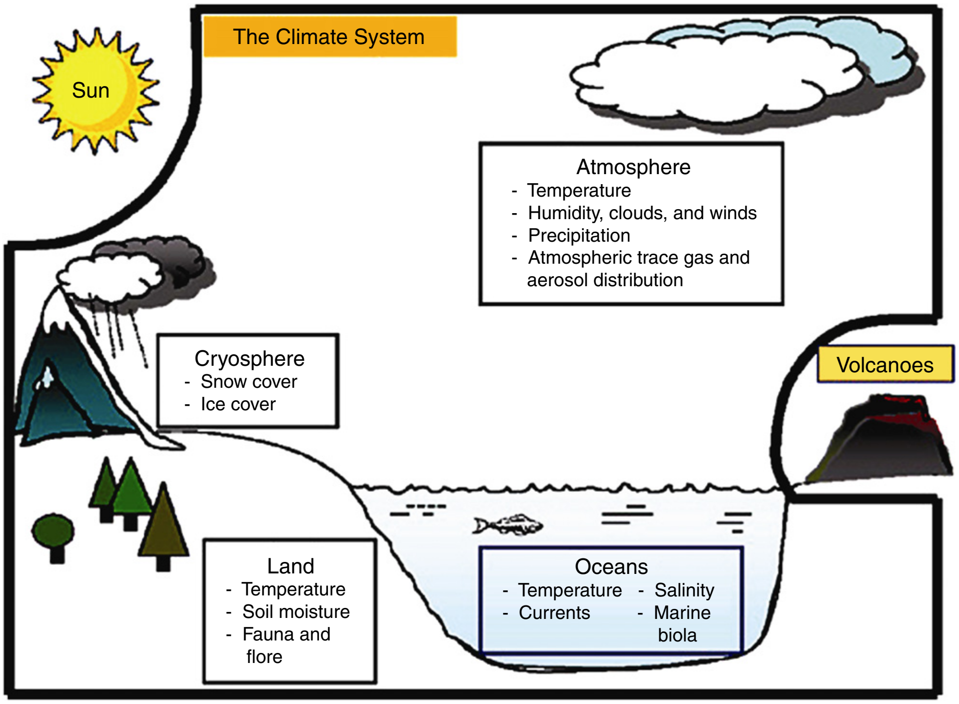
The Climate System
Sun
Atmosphere
- Temperature
- Humidity, clouds, and winds
- Precipitation
- Atmospheric trace gas and aerosol distribution
Cryosphere
- Snow cover
- Ice cover
Volcanoes
Land
- Temperature
- Soil moisture
- Fauna and flore
Oceans
- Temperature
- Currents
- Salinity
- Marine biola

Figure 2 The climate system, consisting of the atmosphere, oceans, land, and cryosphere. Important state variables for each sphere of the climate system are listed in the boxes. For the purposes of this report, the Sun, volcanic emissions, and human-caused emissions of greenhouse gases and changes to the land surface are considered external to the climate system (NRC 2005).

First, climate is never static (Lovejoy and Schertzer 2012). As written in Rial et al. (2004)

> "The Earth's climate system is highly nonlinear: inputs and outputs are not proportional, change is often episodic and abrupt, rather than slow and gradual, and multiple equilibria are the norm."

The assumption of a stable climate system (e.g., the reason for the use of the terminology 'climate stabilization') in the absence of human intervention is a mischaracterization of the behavior of the real climate system. Humans are now adding to the complexity of forcings and feedbacks, but change has always been a part of the climate system. 'Climate change' is, and always has, been occurring. The added word 'change' is, therefore, redundant.

Moreover, there are additional misunderstandings. 'Global warming', which is an increase in the global annual average heat content measured in Joules, is often incorrectly equated to mean 'climate change'. Global warming, however, is just a subset of "climate change."

The term 'climate change', is also being erroneously used to mean only 'anthropogenic caused changes in climate' from nearly 'static' climatic conditions. Frequently, just the human input of greenhouse gases is assumed to be the reason for 'climate change'. For example, NRC (2010) (Climate Stabilization Targets: Emissions, Concentrations, and Impacts Over Decades to Millennia (2010)) states

> "This new report from the National Research Council concludes that emissions of carbon dioxide from the burning of fossil fuels have ushered in a new epoch where human activities will largely determine the evolution of Earth's climate."

Thus, the recommendations to the authors of the volume (not always accepted) were to replace terminology, such as climate change, climate stabilization, and climate disruption, with accurate terminology. When changes in climatic conditions are discussed, it was requested that the actual climate variables (such as temperature, precipitation, length of growing season) that are being altered, be specified. Phrases such as 'changes in regional and global climate statistics' could also be used.

There is a very fundamental reason to limit the use of 'climate change' by the impacts community. Key societal and environmental resources, such as water, food, energy, ecosystem function, and human health respond to climate, not just to an incremental change in the climatic conditions. As noted earlier, the assumption of a stable climate system, in the absence of human intervention, is a mischaracterization of the behavior of the real climate system.

However, some authors retained the use of the terminology 'climate change'. It was acquiesced as long as there was a significant contribution in their chapter to a broad-based assessment of risk to the key resource they were discussing.

Another misused term is 'global change', when really what is almost always meant is a local and/or regional change in the environmental conditions, including from climate. The accurate terminology should be 'environmental change'. The term 'environmental change' is, therefore, preferred rather than 'global change', as the latter terminology is very much a top-down viewpoint. Almost all impacts on key resources are on the local and regional scale.

We also requested the authors start with the risks and factor in the climate threats after thresholds, etc. were first obtained. This was not done in some chapters, but this information can still be extracted from the text. Obtaining the spectrum of risks first is the more inclusive way to assess threats to key resources, and thus, in the view, to prepare the optimal mitigation and adaptation strategies.

For the climate component of risk, the outcome vulnerability (the top-down) approach relies on skillful weather predictions and analyzes with a regional and a local focus. For weather prediction on time periods of days to a week or two, excellent skillful predictions are available for use in outcome vulnerability assessments. On seasonal timescales, there is also some limited predictive skill to apply to outcome vulnerability assessments, particularly for such well-defined weather events such as an El Niño or La Niña (Castro et al. 2007). However, for decadal and multidecadal predictions little, if any, predictive skill has been shown in hindcast climate model predictions of changes in regional weather statistics beyond what is available to the impacts community via the historical, recent paleorecord and a worst case sequence of weather events.

To illustrate the lack of skill, the conclusions from several papers have been summarized. Fyfe et al. (2011) concluded that

> "….for longer term decadal hindcasts a linear trend correction may be required if the model does not reproduce long-term trends. For this reason, we correct for systematic long-term trend biases."

Xu and Yang (2012) find that without tuning from real world observations, the model predictions are in significant error. For example, they found that

> …the traditional dynamic downscaling (TDD) [i.e. without tuning) overestimates precipitation by 0.5-1.5 mm d-1…..The 2-year return level of summer daily maximum temperature simulated by the TDD is underestimated by 2-6°C over the central United States-Canada region."

The paper van Oldenborgh et al. (2012) report just limited predictive skill in two regions of the oceans on the decadal time period, but no regional skill elsewhere, when they conclude that:

> "A 4-model 12-member ensemble of 10-yr hindcasts has been analysed for skill in SST, 2m temperature and precipitation. The main source of skill in temperature is the trend, which is primarily forced by greenhouse gases and aerosols. This trend contributes almost everywhere to the skill. Variation in the global mean temperature around the trend does not have any skill beyond the first year. However, regionally there appears to be skill beyond the trend in the two areas of well-known low-frequency variability: SST in parts of the North Atlantic and Pacific Oceans is predicted better than persistence. A comparison with the CMIP3 ensemble shows that the skill in the northern North Atlantic and eastern Pacific is most likely due to the initialisation, whereas the skill in the subtropical North Atlantic and western North Pacific are probably due to the forcing."

Anagnostopoulos et al. (2010) report that

> "…. local projections do not correlate well with observed measurements. Furthermore, we found that the correlation at a large spatial scale, i.e. the contiguous USA, is worse than [even] at the local scale."

Stephens et al. (2010) wrote

> "models produce precipitation approximately twice as often as that observed and make rainfall far too lightly…..The differences in the character of model precipitation are systemic and have a number of important implications for modeling the coupled Earth system …….little skill in precipitation [is] calculated at individual grid points, and thus applications involving downscaling of grid point precipitation to yet even finer-scale resolution has little foundation and relevance to the real Earth system."

van Haren et al. (2012) concluded from their study with respect to climate model predictions of precipitation that

> "An investigation of precipitation trends in two multi-model ensembles including both global and regional climate models shows that these models fail to reproduce the observed trends….. A quantitative understanding of the causes of these trends is needed so that climate model based projections of future climate can be corrected for these precipitation trend biases…. To conclude, modeled atmospheric circulation and SST trends over the past century are significantly different from the observed ones."

Sun et al. (2012) found that

> "…in global climate models, [t]he radiation sampling error due to infrequent radiation calculations is investigated …….. It is found that…. errors are very large, exceeding 800 W m^{-2} at many non-radiation time steps due to ignoring the effects of clouds…."

There is an important summary of the limitations in multidecadal regional climate predictions in Kundzewicz and Stakhiv (2010) who succinctly conclude that

> "Simply put, the current suite of climate models were not developed to provide the level of accuracy required for adaptation-type analysis."

Since the top-down outcome vulnerability approach depends on skillful decadal and longer regional and local climate predictions, yet they have shown little if any skill, another approach is needed.

For this reason, the volume set of five books presents an alternate approach – the bottom-up, resource-based outcome (contextual) vulnerability perspective. The goal of the set was to focus on the climate component of stress but also consider, in-depth, other environmental and social threats.

The text of the articles is written at a level that allows undergraduate students to understand the material, while providing active researchers with a ready reference resource for information in the respective field.

The questions requested to the authors address with respect to a specific resource were:

1. Why is this resource important? How is it used? To what stakeholders is it valuable?
2. What are the key environmental and social variables that influence this resource?
3. What is the sensitivity of this resource to changes in each of these key variables? This includes, but is not limited to, the sensitivity of the resource to climate variations and change on short (e.g., days), medium (e.g., seasons), and long (e.g., multidecadal) timescales.
4. What changes (thresholds) in these key variables would have to occur to result in a negative (or positive) response to this resource?
5. What are the best estimates of the probabilities for these changes to occur? What tools are available to quantify the effect of these changes? Can these estimates be skillfully predicted?
6. What actions (adaptation/mitigation) can be undertaken in order to minimize or eliminate the negative consequences of these changes (or to optimize a positive response)?
7. What are specific recommendations for policymakers and other stakeholders?

There are also overview chapters that discuss the science of the resource.

Several authors insisted on focusing on the use of the outcome vulnerability (top-down) approach based on the multidecadal GCM projections (statistically or dynamically downscaled) as the starting point of their chapters. The chapters were accepted, despite this shortcoming, because when they finally discussed adaptation in their text, they did present the broader-based bottom-up focus that is the centerpiece of the volume. Readers,

however, need to be aware that the top-down, GCM scenarios are only a subset, at best, of what is plausible in the coming decades. Multidecadal predictions of changes in regional and local climate statistics have not shown skill when run in a hindcast mode for the past several decades.

In summary, the goal of the five-volume set of books is to document the value of a bottom-up, resource-based assessment of risk to key resources, as illustrated schematically in Figure 3a–e. Most, but not all, authors accepted this framework. This can be assessed without having any predictability on

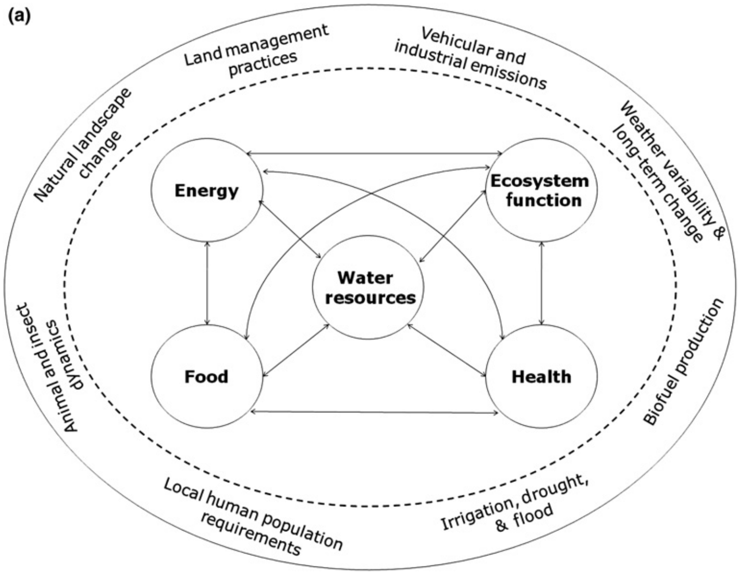
(a)
Land management practices
Vehicular and industrial emissions
Weather variability & long-term change
Biofuel production
Irrigation, drought, & flood
Local human population requirements
Animal and insect dynamics
Natural landscape change
Energy
Ecosystem function
Water resources
Food
Health

Figure 3a Contextual vulnerability for water resources (Hossain: Editor)

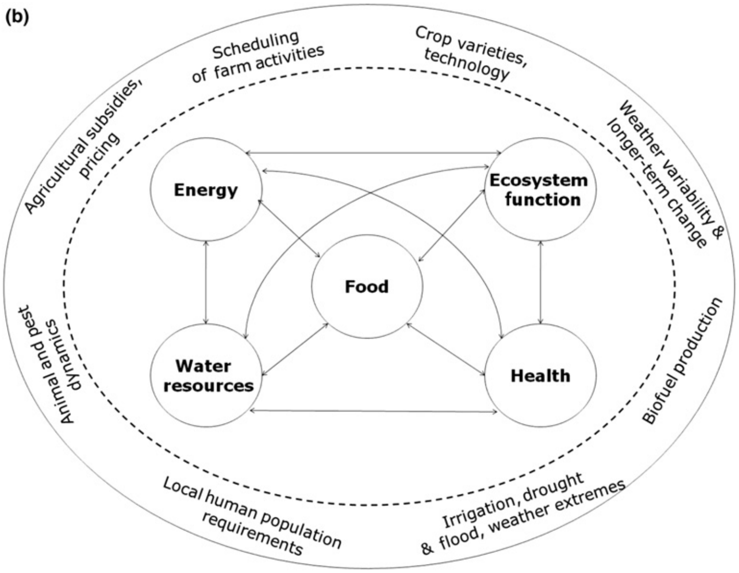
(b)
Scheduling of farm activities
Crop varieties, technology
Weather variability & longer-term change
Biofuel production
Irrigation, drought & flood, weather extremes
Local human population requirements
Animal and pest dynamics
Agricultural subsidies, pricing
Energy
Ecosystem function
Food
Water resources
Health

Figure 3b Contextual vulnerability for food (Niyogi: Editor).

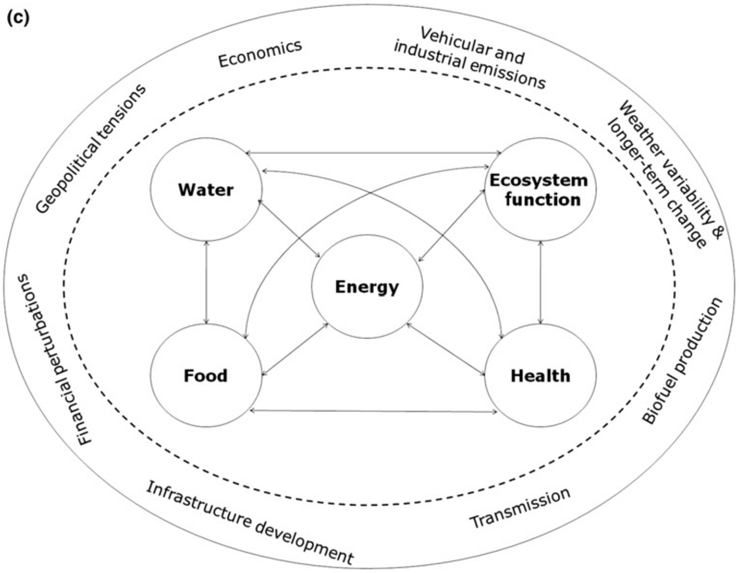
(c)
Economics
Vehicular and industrial emissions
Geopolitical tensions
Weather variability & longer-term change
Water
Ecosystem function
Energy
Food
Health
Financial perturbations
Biofuel production
Infrastructure development
Transmission

Figure 3c Contextual vulnerability for energy (Kallos: Editor).

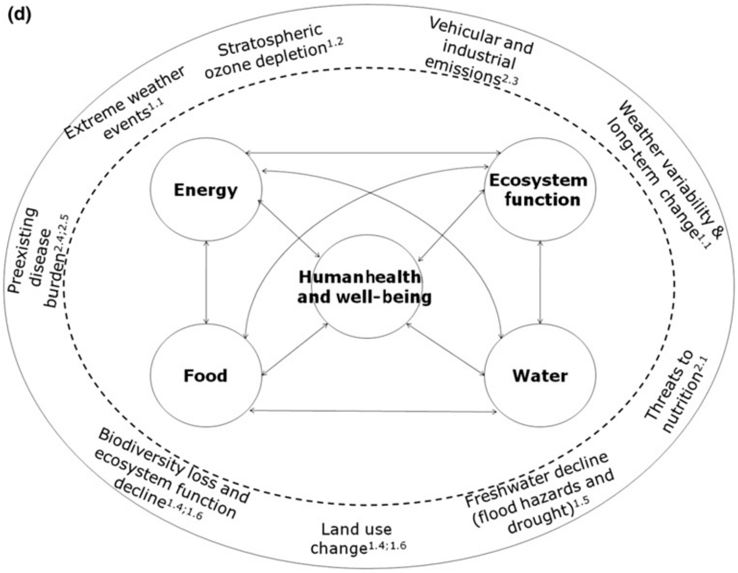
(d)
Stratospheric ozone depletion$^{1.2}$
Vehicular and industrial emissions$^{2.3}$
Extreme weather events$^{1.1}$
Weather variability & long-term change$^{1.1}$
Energy
Ecosystem function
Preexisting disease burden$^{2.4;2.5}$
Humanhealth and well-being
Food
Water
Threats to nutrition$^{2.1}$
Biodiversity loss and ecosystem function decline$^{1.4;1.6}$
Land use change$^{1.4;1.6}$
Freshwater decline (flood hazards and drought)$^{1.5}$

Figure 3d Contextual vulnerability for human health and well-being (Adegoke and Wright Editors).

multidecadal time periods. It is an alternative (and more inclusive) perspective than the IPCC top-down outcome vulnerability approach which starts with the GCMs as the overarching framework. In the bottom-up approach, the scenarios from the GCM predictions should only enter after the specific threats to the resources are determined and even then, they provide, at best, a limited set of insights into what is possible.

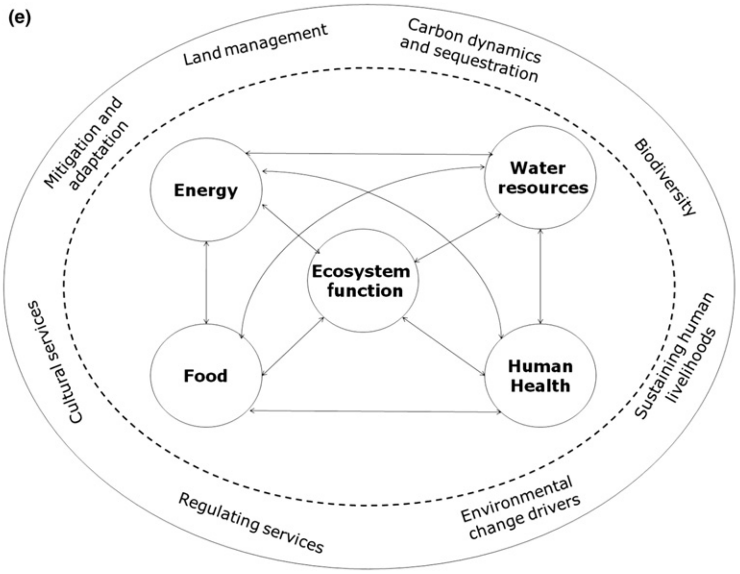
(e)
Land management
Carbon dynamics and sequestration
Biodiversity
Sustaining human livelihoods
Environmental change drivers
Regulating services
Cultural services
Mitigation and adaptation
Energy
Water resources
Ecosystem function
Food
Human Health

Figure 3e Contextual vulnerability for ecosystem function (Seastedt and Suding; Editors).

We look forward to feedback from the readers.

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Jimmy Adegoke,
Faisal Hossain,
George Kallos,
Dev Niyogi,
Timothy Seastedt,
Katharine Suding,
Caradee Y. Wright and
Dallas Staley

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Preface - Vulnerability of Human Health to Climate

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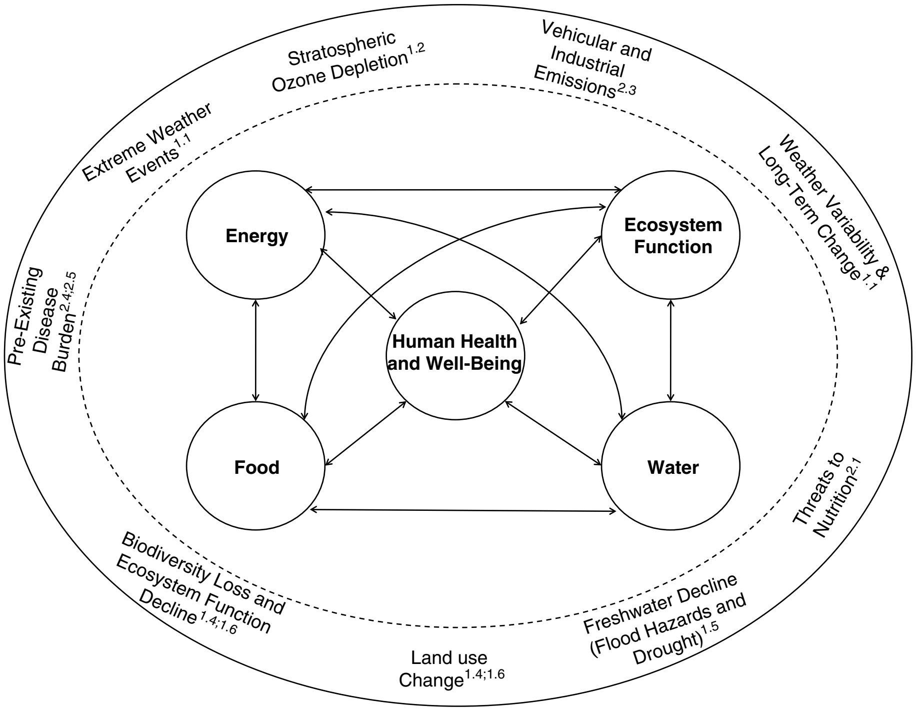
Human health, defined as the complete state of physical, social, and mental well-being and not merely the absence of illness, disease, or infirmity, is as vital a resource as water, food, or energy. Health underpins the economy of modern societies, providing employment for many in the health-care sector, and is an important driver of economic growth, accounting for a significant portion of the total expenditure as percentage of the gross domestic product in most countries. While a robust health-care system is needed to support a healthy society, broader actions to reduce social risk are vitally important, including efforts to reduce disparities in wealth, employment, equity, education, and housing.

Since the turn of the century, the public health landscape has become increasingly complex: old problems persist and new problems emerge – sometimes in unexpected places – and the importance of understanding economic, social, political, and environmental determinants of health has become more crucial. With health is now appreciated as a key driver of socioeconomic progress, commitment to the Millennium Development Goals (MDGs) will help to ensure that communities work their way out of poverty, contribute toward society, and enjoy improved quality of life while reducing their vulnerability and enhancing their coping mechanisms. Globally, progress toward the health-related MDGs and targets set for 2015 seem promising, but significant challenges remain because progress in addressing the needs of the most vulnerable has been slow. The MDGs, adopted as part of the UN Millennium Declaration by 189 heads of state in 2000, articulate targets for countries to reduce poverty and hunger; tackle ill-health, gender inequality, lack of education, and environmental degradation; and improve access to clean water. In 2011, reports of indicators measured suggested that, globally, fewer children were dying, fewer children were underweight, fewer people were contracting HIV, tuberculosis treatment was more successful, and more people had safe drinking water but not adequate sanitation. This progress was not evenly spread across all countries, with some making excellent progress and others falling behind, especially those countries affected by the HIV epidemic, conflict, and poverty.

Within countries, the capacity of communities to cope with health-related risks differs significantly; thus, communities have different susceptibilities to illness, disease, and infirmity. Their vulnerability may be further complicated by social, economic, and environmental issues. Poverty and inequity are major challenges to public health; environmental stresses such as droughts, excessive heat, and floods are a compounding challenge. Climate-induced vulnerability is one of several threats to public health with several direct and indirect impacts. These range from the direct physiological effects of heat and cold on the human body to adverse effects on livelihoods resulting in poor health outcomes. Some of the direct


Stratospheric Ozone Depletion$^{1.2}$
Vehicular and Industrial Emissions$^{2.3}$
Extreme Weather Events$^{1.1}$
Weather Variability & Long-Term Change$^{1.1}$
Pre-Existing Disease Burden$^{2.4;2.5}$
Energy
Ecosystem Function
Human Health and Well-Being
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Water
Threats to Nutrition$^{2.1}$
Biodiversity Loss and Ecosystem Function Decline$^{1.4;1.6}$
Land use Change$^{1.4;1.6}$
Freshwater Decline (Flood Hazards and Drought)$^{1.5}$

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climate-related health effects, risks, and impacts include water- and food-borne diseases and heat-related morbidity and mortality. Although the editors of the Health Volume of the Climate Encyclopaedia attempted to achieve comprehensive coverage of climate-related health impacts, the contributions included in the volume, of course, reflect the expertise and interests of the team of health and environmental experts that authored the chapters.

The Health Volume of the Climate Encyclopaedia was compiled in three parts. Part one considers cross-cutting environmental threats to human health. These threats include extreme weather events, stratospheric ozone depletion, sea level rise, ecosystem change, floods, droughts, and biodiversity loss. Part two focuses on the relevant health effects, impacts, and risks posed by these threats. Health impacts explored in this section include food-borne disease and malnutrition, heat- and cold-related morbidity and mortality, urban air pollution, and respiratory allergy, HIV, TB, and occupational health. Part three uses the case study approach to examine theme- or place-specific topics that offer unique insights, which also have broader relevance. The section includes three case studies. The first is a bibliometric analysis of keywords 'human health in a changing climate' in academic literature over the past three decades, showing that this topic has become an attractive research and media topic. The second case study explores the food insecurities experienced by Pacific Island countries to highlight the complexity of vulnerabilities over and above those related to climate vulnerability. The third case study focuses on Africa and shows how health outcomes are a key determinant of social or contextual vulnerability using a South African community-scale example.

Given the complexity of factors that influence human health, assessing health impacts related to climate clearly poses a difficult challenge. Nevertheless, we sought in this volume to present a well-rounded picture of both the threats and risks to human health posed by climate, in the widest possible context and applying a contextual vulnerability approach, thereby providing material to aid in public education, planning, and decision making at all levels. A great effort, for which the editors are deeply grateful, was made by all of the Health Volume authors to apply a contextual vulnerability and a bottom-up approach in the presentation of their subject material. Our hope is that this will give readers a holistic understanding of each issue and also make it easier for decision makers in the health sector to incorporate ideas and concepts presented in this volume in their community risk assessment and adaptation planning efforts. The editors also wish to acknowledge and thank all the anonymous chapter reviewers for their time and effort to meticulously review the content for technical and scientific accuracy.

1.01 Extreme Weather Events

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1.01.1 Introduction

The term ‘global warming’ is largely recognized by the general public as an increasing annual average global surface temperature. This is often perceived to be the only result of the increased emissions of greenhouse gases from human activities. ‘Climate change’ is now the term often used to describe the effects of these emissions on our environment. Global warming is a part of climate change, along with changes in weather patterns, sea level, and so on. However, regional temperature extremes (cold surges and heat waves), in association with increased variability in severe weather events such as hurricanes, are the more important aspects of climate change. These affect societies and ecosystems more directly than does the global climate average.

As with all weather phenomena, the impacts of climate will depend on the systems in which it occurs. Weather-related events and climatic extremes can have disastrous effects on the environment, human society, and infrastructure. For human systems, much will depend on our ability to adapt to these events and extremes. Changes in crops, infrastructure designs, and many other aspects of society can greatly increase resilience to adverse weather as well as reduce the risk to climate variability and long-term change. Yet the capacity to adapt to climate is much greater in particular groups, for example, developed countries as opposed to underdeveloped countries, and so the effects of climate and extreme weather events vary regionally and even between groups within a particular society. This chapter examines the effects of extreme weather events on human health and health systems, people’s vulnerabilities to extreme weather, and their coping capacities.

1.01.1.1 Climate and Extreme Weather Events

Climate change includes a change in the state of the climate that can be identified (e.g., using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. It refers to any change in climate over time, whether due to natural variability or as a result of human activity (IPCC 2007). Extreme weather is weather that is outside of what is normally expected for a particular location and thus is rare for that area. Therefore, these areas are often not prepared for these events, and extreme weather events can cause severe damage to the environment, infrastructure, and human society. This can be costly both in a monetary sense and to life. A significant effect of humans on the climate has been accepted by most of the scientific community. Such a human effect could increase the frequency, severity, duration, or aerial extent of extreme weather events. However, actual trends in extreme weather events are difficult to determine, given the complications such as lack of long-term climate data, spatial variation in data available, and changes or differences in public perception (e.g., there is an increase in media access, thus the public is more aware of extreme weather event occurrences).

Determining trends in extreme weather events is also difficult because extreme events by definition are rare. However, there is empirical evidence that extreme weather damage has become more frequent and/or more severe (Figure 1) and it is now concluded that the reason for most of the increased damage is socioeconomic, not climate, at least up to the present. There has been a dramatic increase in the number of disaster events over the past decade and a geometric increase in the number of people affected since the beginning of reliable recording in the 1960s

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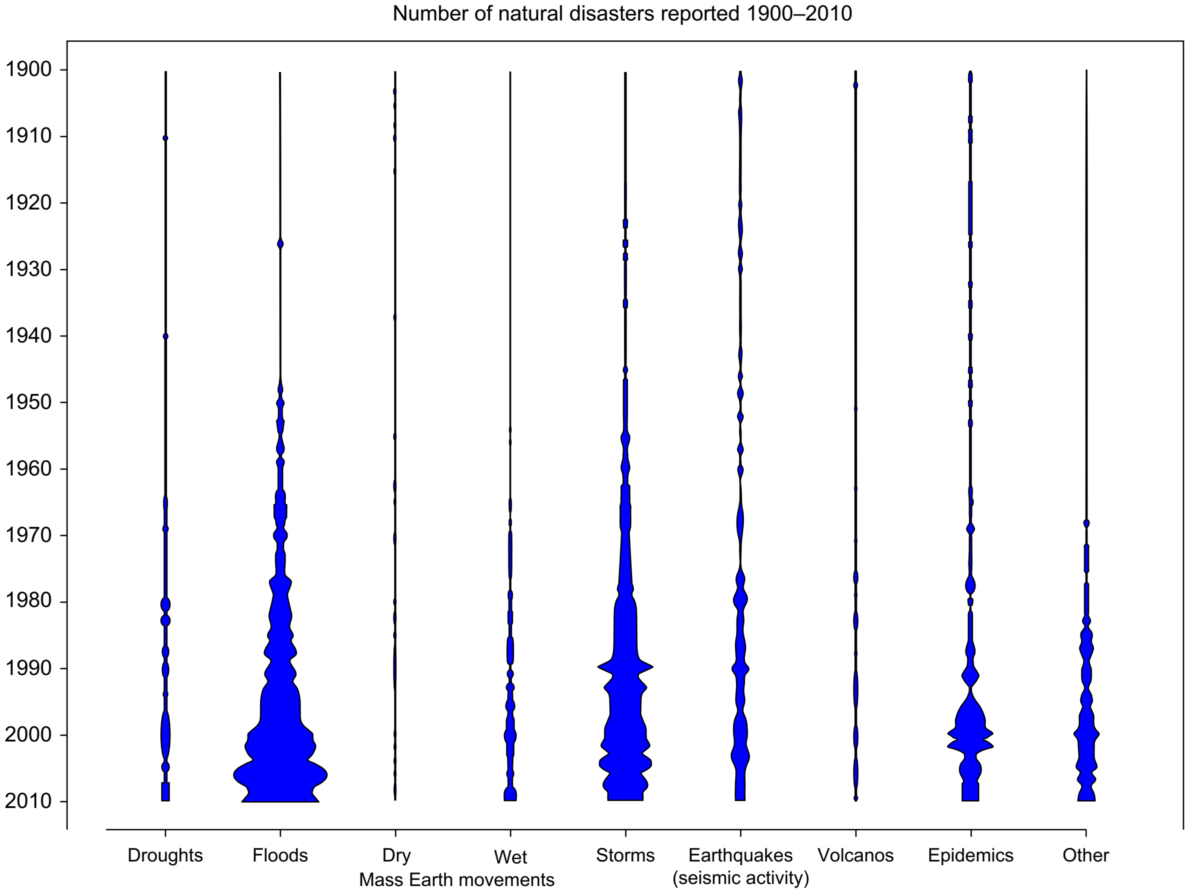

Figure 1 Number of natural disasters reported 1900–2010. Source: EM-DAT: The OFDA/CRED international disaster Database – www.emdat.be, Université Catholique de Louvain, Brussels (Belgium).

(IFRC 2003). There have been claims of increasing frequency of heavy precipitation events in the midlatitude regions that has been linked to global warming (Groisman et al. 2005).

Extreme precipitation events may lead to more intense and frequent river flooding. In other areas, for example, Sahel, the Mediterranean region, southern Africa, and parts of southern Asia, precipitation has decreased. Globally, the area affected by drought has likely increased since the 1970s (IPCC 2007). While there is little research on extreme temperature patterns, there has been an increase in the global mean surface air temperature of about 0.5 °C since the start of the twentieth century, and this is linked to a rise in the minimum daily temperature (Easterling and Wehner 2009). Consistent with this is the trend that in many parts of the world, including Australia, China, Europe, New Zealand, and the United States, there are fewer days with frost. However, this increase in minimum temperature may be due just to a change in the vertical mixing of heat near the surface at night rather than heating (Zhou et al. 2012; McNider 2007).

1.01.2 Extreme Weather Event Effects on Human Health

Extreme weather events such as flooding, drought, and hurricanes can have direct and indirect effects on human health. Effects such as adverse physical health outcomes are related directly to weather, for example, drowning and injuries in floods, injuries and deaths caused by falling debris from structures as they are destroyed by tornados, or increased morbidity and mortality during heat waves or cold snaps. Indirect effects include outcomes related to extreme weather and involve not only physical health outcomes, for example, vector-, food-, and water borne diseases, but also mental health stress or illness, loss of income, compromised nutrition, and social disruption. Infrastructure may be damaged, and so sanitation and access to clean safe drinking water is compromised. The existing infrastructure may not be able to cope with excessive demands during particularly high rainfall events; studies have shown that extreme wet weather events are responsible for a large number of waterborne disease outbreaks in the United States (Curriero et al. 2001).

Displacement of people and permanent migration from flooded areas or areas devastated by droughts are a serious concern, especially for those in rural areas reliant on crops for their livelihood or for those who cannot afford or do not have the means to relocate successfully, for example, those who do not have insurance to fund relocation or those without the necessary education/skills to find work elsewhere. Uncertainty surrounding climate can place mental and economic strain on people, again particularly affecting groups such as farmers whose crop production is dependent on a particular climate for success. Certain groups and individuals within communities will be more vulnerable to extreme weather event effects on their health and well-being, thus differences exist not only because of the nature of the weather event but also because of the population or area that is affected.

1.01.3 At-Risk Populations

Developing nations, urban populations, communities with lower socioeconomic status, and certain individuals, such as the young, a growing aging population, the mentally ill, those with existing medical conditions, and the homeless, are likely to be more vulnerable to negative effects of extreme weather events. Assessing vulnerability is difficult, because, as the United Nations Development Program (UNDP) states: "The social and economic processes that produce vulnerability and contribute to disaster risk are complex" (UNDP 2004). Climate variability and any associated increase in the frequency and magnitude of extreme weather events would exacerbate the problems already faced by developing countries and could undermine the progress of development already made.

Underdeveloped countries have an unequivocal burden of disaster-related mortality – although only 11% of people exposed to natural disasters live in developing countries, they account for 53% of disaster-related deaths (UNDP 2004). Most of the 48 least developed countries (LDCs) are in Africa (33 nations) and Asia (14 nations), whose collective populations comprise more than 880 million people, approximately 12% of the world population. The identification of LDCs is based on three criteria: per capita gross national income, human assets, and economic vulnerability to external shocks (UN http://www.unohrlls.org/en/ldc/25/). The LDC criterion also excludes large economies with populations exceeding 75 million. However, although India is not on this list of LDCs because of its estimated population of 1.17 billion, it is commonly acknowledged to be a developing country. Despite having the world's 12th largest economy, more than half of India's population depend on agriculture for their livelihood and 700 million Indians live on $2 per day or less. Inadequate infrastructure and health care systems in these nations may leave the people unable to cope with and respond to extreme weather events. Many of these developing countries rely heavily on subsistence agriculture (Reed 1997), and so extreme weather events such as drought and increased precipitation will have a larger impact, potentially resulting in famine and widespread mortality.

The urban population (3.42 billion) had surpassed the number of people living in rural areas (3.41 billion) by 2009, and this rapid growth is expected to continue in the next few decades, especially in Africa and Asia where the urban population is expected to double between 2000 and 2030. However, there is a disproportionate number of urban dwellers in developed as opposed to underdeveloped countries (UNFPA 2011; UNDP 2010). Urbanization started in today's more developed regions, and urbanization levels remain high in the more developed nations. For example, in 2009, Australia, New Zealand, and Northern America had urbanization levels grater than 80%. By 2050, Australia, New Zealand, and Northern America are all expected to be over 90% urban, whereas Europe's level of urbanization is projected to be lower, at 84% (UNDP 2010). Because wind velocities are generally lower in urban cities than in open areas, air temperature and mean radiation temperature are often higher, and thus urban populations may be more exposed to higher temperatures than rural populations. Hughes and Balling (1996) have shown that at least half of long-term warming in South Africa in the past 30 years is due to urbanization and that the diurnal temperature range was decreasing in urban areas. Urban dwellers are reliant on centralized water and power supplies, sanitation, and health care systems, and so they are particularly at risk when extreme weather events compromise infrastructure integrity.

Children are more vulnerable to negative effects of extreme weather events compared to adults for several reasons, including small body size, lower body strength, underdeveloped immune system, and lower ability for fast cognitive thinking in emergency situations. Children are more susceptible than adults to air pollutants as they have narrow airways and underdeveloped respiratory systems. When they are playing outside, exercise increases breathing through the mouth, bypassing the filtering of the nose and so pollutants directly enter the lungs.

Older people and children are more vulnerable to the effects of temperature extremes and have a significantly higher mortality risk in extreme weather events. The elderly (65 years and older) accounted for 72% of all heat-related deaths due to the mid-July 1995 heat wave in Chicago, USA (Whitman et al. 1997). Infants lose body heat more easily than adults; in addition, infants cannot make enough body heat by shivering. Children are more prone to develop hypothermia (lowered body temperature) when the body's rate of heat loss is greater than the rate of heat production. Children also have a relatively larger body surface area that contributes to more rapid heat loss. They have smaller bodies with less muscle mass and tone than adults, which make them more vulnerable to drowning in floods. They rehydrate less efficiently than adults and so are more likely to dehydrate under drought conditions or when there is a lack of drinking water, such as when infrastructure is compromised because of extreme events such as flooding, hurricanes, and storms. Children's immune systems are less developed than those of adults, and so they may not be able to fight off infectious diseases, which are more likely when there is lack of potable water or sanitation or when many people are packed in temporary shelters.

Societal effects and preexisting conditions compound negative health effects of extreme weather events on the elderly, so they are more likely to suffer negative health effects from climate stress and vector-borne diseases (Rey et al. 2007; Geller and Zenick 2005; Haq et al. 2008). People who are poorer, have no education, have less access to transportation, and are more disconnected socially will be at greater risk for negative outcomes in natural disasters (Son et al. 2012; Haq et al. 2008). Susceptibility to heat may be increased for the elderly, female, and unmarried, with additional risk factors being preexisting health conditions such as chronic pulmonary disease, diabetes, psychiatric disorders, and pulmonary and cardiovascular conditions (Schifano et al. 2009; Bouchama 2004); however, these differences in susceptibility factors are not universal, and therefore risk factors need to be identified at the local level in order to manage and prevent morbidity and mortality from heat in these groups.

Older people are also more likely to die as a result of hurricanes. Hurricane Katrina was the deadliest hurricane to make landfall in the United States since 1928, with approximately 1000 deaths directly attributed to it. The risk of death from Katrina, in which drowning was the most common cause of death, increased with age – older people were more affected (Brunkard et al. 2008; Jonkman et al. 2009). This is not surprising, given that many elderly people have restricted physical mobility, may lack personal transportation, and may have underlying conditions that predispose them to indirect effects of stress and shock. This was the case in Hurricane Andrew, wherein the elderly had higher mortality because of indirect causes (Combs et al. 1996). Evacuating elderly people with medical conditions can pose a risk in itself. Housing them in local shelters is also potentially risky because of crowded conditions, reduced sanitation, and lack of supplies. Evacuee shelters and emergency medical care centers may not be equipped to care for and treat those with disabilities or chronic diseases. Vulnerabilities of the elderly are complex, because of confounding factors such as race, education, gender, and so on, and also because they may have disabilities or chronic health conditions. For example, generally, the elderly living in coastal areas vulnerable to hurricanes or flooding are at higher risk than those living inland; however, wealth may mollify their vulnerability. For example, wealthy elderly living in Florida barrier islands were found to be less socially vulnerable despite the high risk owing to their location, whereas those living inland, while having lower physical risk, were more likely poorer, which increased their overall risk (Wang and Yarnal 2012).

Vulnerability to disaster is difficult to measure as it is very complex, especially so are the effects on mental health. Although studies have shown that factors such as socioeconomic status, age, and displacement affect vulnerability to mental health disorders as a result of extreme weather events, there are disparities in the data. Kessler et al. (2008) found that mental health outcomes from Hurricane Katrina were only weakly related to sociodemographic factors, indicating a widespread effect of this hurricane even 2 years after the event. Perhaps in such an extensive massive disaster (Katrina devastated an area equivalent to the size of Great Britain), all people, not just high-risk groups, will be vulnerable.

To mitigate vulnerability to extreme weather events, vulnerable nations, communities, and individuals first need to be identified. However, there are inherent scientific, social, and political problems associated with coming up with such lists. An individual's vulnerability to extreme weather events is complex and dependent on a number of interacting factors. Institutions vested in protecting human health must make decisions regarding where to place their efforts and resources. Funds and resources available to address extreme weather preparedness and response are limited and so must be targeted toward those most at risk.

1.01.4 Temperature Extremes

1.01.4.1 Heat Waves and Droughts

Heat is associated with increased morbidity and mortality, especially among the elderly (Hajat et al. 2002; Pattenden et al. 2003; Rey et al. 2007). Defining what constitutes a 'hot day' or a 'heat wave' is difficult because climate, and thus acclimatization, varies with location. A hot day occurs when the temperature exceeds the 90th–95th percentile of the local daily temperature (IPCC 2007; Jones et al. 1999; Pan and Zhai 2002; Yan et al. 2002; Hua et al. 2006; Fang et al. 2008). A heat wave is generally defined to be when hot days persist for more than 2–5 days. The frequency of extremely hot days in temperate zones doubles for every 2–3 °C rise in temperature during an average summer (Bunyavanich et al. 2003). Prolonged exposure to high temperatures can cause heat cramps, heat exhaustion, and heat stroke. Symptoms of heat exhaustion include heavy sweating, nausea, lightheadedness, and feeling faint. Symptoms of heat stroke include a body temperature of 40 °C (104 °F) or more; lack of sweating, nausea, and vomiting; flushed skin; rapid breathing; racing heartbeat; headache; confusion; unconsciousness; and muscle cramps or weakness. People most vulnerable to heat wave-associated mortality include the elderly, women, and those with certain conditions such as respiratory system diseases, nervous system diseases, mental disorders, infectious diseases, and endocrine and nutritional diseases (Rey et al. 2007).

There is an apparent trend toward increasing hot days and heat waves in recent years. Ding et al. (2010) investigated hot days and heat waves in China during 1961–2007 and found an increasing trend of hot days after the 1990s in all regions of that country. However, there are regional differences; for example, hot days and heat waves most frequently occur in northwestern and southeastern China. These spatial differences highlight the problem that these extreme weather events typically affect smaller areas but to a great extent and thus the health, societal, and economic burdens may be carried by a local area. A record-breaking heat wave occurred in Europe in the summer of 2003, with temperatures more than 3 °C above the average level of 1961–90, which resulted in widespread droughts, crop losses, and more than 22 000 heat-related deaths across Europe (Christoph and Gerd 2004; Levinson and Waple 2004; Rey et al. 2007). This heat wave was found to be due to a stagnant high pressure region over the area whose effect was magnified by a drier-than-average land surface (Chase et al. 2006, 2008; Connolley 2008). The Moscow heat wave of 2010 was analyzed by Dole et al. (2011) who concluded that this heat wave was mainly because of internal atmospheric dynamical processes that produced and maintained a strong and long-lived blocking event and that similar atmospheric patterns have occurred with prior heat waves in this region.

The Chicago heat wave, occurring between 12 July and 16 July 1995, was the cause of almost 700 deaths. Temperatures ranged between 93 °F and 104 °F, with the highest temperature recorded on July 13, with a heat index of 119 °F (Donoghue et al. 1995). The event affected predominantly high-risk populations, such as low-income and uneducated families, people with preexisting medical conditions, and people who were constrained to bed with need for assistance from visiting medical care. Previous studies have demonstrated that the main factors leading to death during heat wave are cardiovascular diseases (Kilbourne et al. 1982). A study investigating the cause-specific mortalities over a 50-day period in the Chicago area (with midpoint around the occurrence of the heat wave) confirmed that sudden death and cardiovascular causes were recorded as the predominant reason for deaths on most death certificates (Kaiser et al. 2007). The same research also confirmed that poor less-educated populations were highly affected by the heat wave. Some of the families included people in urban areas with no previous education on protective measures against extreme weather events as well as poor living conditions without any cooling system, such as air-conditioners or fans. Such extreme weather events confirm that socioeconomic status could play a crucial role in determining the likelihood of survival among different populations.

More than half of all deaths associated with natural hazards are drought related, and drought is second only to floods in terms of the number of people affected (Below et al. 2007). Droughts can also have secondary impacts such as reduced water availability, wildfire danger, and destruction of agricultural crops (and hence reduced food availability). Droughts are also difficult to define. Media reports can be misleading especially since droughts can be very localized and thus have major effects on small areas that may be perceived to be more widespread than they actually are. One example is the drought of 2002 in Colorado, USA. the onset of drought in 2002, the preceeding years showed below-average snowfall and higher temperatures during the winter seasons. In 2000, drought contributed to severe wildfires during the summer months. The low precipitation during the years preceding 2002 brought depletion of soil moisture and surface water supplies because of high evaporation rates as a result of higher-than-average temperatures (Doesken and Pielke Sr 2008; Pielke et al. 2005). During the spring months of 2002, the usual spring storms for the area did not occur and temperatures rose to record high levels. Wildfires, water depletion, and crop deterioration were the outcome of the drought, as well as massive die-off of dominant tree species in an area spanning approximately 12 000 km^2 (Breshears et al. 2005). Implications associated with reduction of forest mass bring along ecological consequences, such as carbon emissions, further temperatures rises, soil erosion, and loss of ecosystem previously supported by trees (Luo 2007; Breshears and Allen 2002). The 2011 heat wave in Russia fueled disastrous wildfires and killed nearly 56 000 people as result of heat and increased air pollution and destroyed one-third of the country's wheat crop. Heat waves and drought not only cause death, particularly of more susceptible people such as the very young and the elderly, but also can have wide-ranging devastating effects on food sources.

1.01.4.2 Extreme Cold

Severe cold is a weather pattern that can have deleterious effects on an impacted region and accounts for high levels of mortality during the winter months in the temperate regions of the planet. Exposure to extremely low temperatures presents high health risk to vulnerable populations such as children, elderly, homeless, intoxicated people, and those with preexisting health conditions, such as ischemic heart disease. In addition, severe cold could impact the economy of a region by immobilization because of heavy snowfall or could affect energy demands, production, agriculture, and livestock. It has been estimated that severe cold accounts for 3–18% of the total annual mortality in economically developed countries during the winter months (Sakamoto-Momiyama 1977; Rosenwaike 1966; Curwen 1990). Records collected for the years 1979 through 2002 indicate that extreme cold is the number one cause of deaths due to weather-related events in the United States, outnumbering other weather extremes such as hurricanes, extreme heat, floods, droughts, tornados, and lightening (Goklany 2007). In the United States, it is estimated that the annual deaths related to extreme cold are 0.8% of the average annual deaths (Deschenes and Moretti 2007).

Typically, severe cold events are followed by an increase in coronary heart disease mortality, cerebrovascular accidents, and respiratory diseases. The normal deep core body temperature is generally maintained at a steady 37 °C (Lloyd 1994). Heat is generated through the body's normal metabolism, and temperature is maintained at a steady value by the thermostatic mechanism in the hypothalamus (Clark et al. 1939). Metabolic or environmental factors can influence body temperature, and beyond certain limits the body experiences either heat stroke or hypothermia. When body temperature begins to drop, superficial and limb blood vessels constrict, thus conserving heat by reducing the difference between skin and environmental temperatures. If the core temperature falls below 35 °C and the rate of heat loss from the body exceeds the rate at which the body is producing heat, individuals are considered to be experiencing hypothermia (Danzl and Pozos 1994; Duguid et al. 1961; Larach 1995; Lloyd 1994). Below 35 °C, physiologic responses to reduce heat loss through radiation, conduction, convection, respiration, and evaporation are very limited because of the failure of the coordinated system to achieve thermoregulation (Hanania and Zimmerman 1999; Mills 1980; Paton 1983).

Hypothermia has four subdivisions: mild, 32–35 °C; moderate, 28–32 °C; severe, 20–28 °C; and profound, at less than 20 °C (Jolly and Ghezzi 1992). During cold months, cases related to hypothermia increase and deleterious effects from it can spread to multiple organ systems, such as renal, cardiac, and central nervous systems (Herity et al. 1991; Ulrich and Rathlev 2004). Heart-related deaths due to severe cold are a result of rising blood pressure because of cold temperatures and an increased chance of blood clots because of the rise of protein levels in the blood. Moreover, as a result of cold temperatures, oxygen supplies to the heart can be reduced due to restricted blood flow from coronary artery spasms (Nabel et al. 1988). Severe cold can have deleterious effect on people with ischemic heart disease, which is characterized by reduced blood supply to the heart. For example, in England and Wales, mortality is 50% higher in winter than in summer and deaths related to ischemic heart disease increase by 20 000 in winter months (Rose 1966; Pell and Cobbe 1999). Extremes such as blizzards during the winter months can drastically increase mortality rates among people with ischemic heart disease. A study conducted in eastern Massachusetts examining death certificates after six blizzards in 1974–78 reported that after a 'blizzard week,' mortality was 8% higher than in preceding (control) weeks. In addition, deaths from ischemic heart disease accounted for 90% of the excess deaths for the same weeks (Glass and Zack 1979).

The risk of upper and lower respiratory tract infections also peaks during the winter season (Mourtzoukou and Falagas 2007; Eccles 2002; Mäkinen et al. 2009). Most studies suggest that susceptibility to infection could be related to suppressed immune responses from vasoconstriction in the respiratory tract mucosa because of lower core body temperature from inhaled cold air and cooling of the body surface. Other studies suggest that indoor crowding during the winter months promotes transmission of pathogens. Further studies propose that seasonal exposure to cold air causes an increase in the incidence of upper respiratory tract infections due to cooling of the nasal airway (Eccles 2002).

Shelter, heating, and warm clothes are typical ways to avoid morbidity and mortality due to cold weather extremes. Those who are in lower socioeconomic groups are more likely to suffer from extreme cold because they lack these essentials. People who are acclimatized to cold temperatures by living in areas that commonly experience cold weather will not only be better able to cope physiologically with cold extremes but also typically have adequate heating systems and protective clothing readily available.

1.01.5 Extreme Precipitation Events

1.01.5.1 Extreme Rainfall and Flooding

A flood is an overflow of a huge amount of water that submerges normally dry land. There are several types of floods: riverine floods caused by excessively heavy rains on to rivers or other types of waterways, estuarine floods caused by sea tidal surges and storm winds, and coastal floods caused by natural disasters including typhoons, high tides, wind storms, and tsunamis (Rappaport 2000). Floods are one of the most common natural disasters, and each year they cause an enormous amount of damage all over the globe. Moreover, floods are one of the leading causes of death each year compared to other natural disasters, accounting for an estimated 40% of all natural disasters (Howard et al. 1996). An estimated total of 1816 worldwide freshwater floods (e.g., river floods, flash floods (damaged dams), or drainage floods) affected more than 2.2 billion persons between 1975 and 2002, and the death toll was over 17 500 (Jonkman 2005). The same study showed that Asia topped the list with the highest amount of impacts from river floods. In the summer of 2010, one-fifth of Pakistan was under water. Over 20 million people were affected by flooding that ran the length of the country along the Indus River, destroyed more than 1.6 million acres of crops, and resulted in millions becoming homeless.

The economic loss from floods is also very high. Impaired infrastructure as a result of floods includes damage or collapse of health center, office, and residential buildings and damage to bridges, roads, and railroads. Floods can greatly impair agricultural production and supply by submerging and killing crops, spoiling produce, removing topsoil from farmlands, and affecting future cultivation.

Multiple environmental consequences can result after flooding from the spread of waterborne pathogens and infectious diseases. In the event of flooding, there is a high risk of damages to water purification and sewage disposal systems. Access to adequate water supplies could be limited because of contamination from fecal materials or dislodgement of toxic chemicals (Wilder-Smith 2005). Open wounds could be easily infected with opportunistic skin pathogens and freshwater- or seawater-borne pathogens.

Coastal floods contribute to the highest mortality after windstorm events including hurricanes, cyclones, and typhoons (Rappaport 2000). Storms like these are characterized by severe flood effects and often appear without warning, with little time for evacuation. Densely populated coastal countries, such as Bangladesh, have been severely impacted over the past decade because of its geographical setting (in the path of tropical cyclones), wide and shallow continental shelf, and the funneling shape of the coast (Karim and Mimura 2008; Das 1972; Murty et al. 1986). Cyclones in 1970 and 1991 have caused at least 500 000 and 138 000 deaths, respectively (Haque 1997; Karim and Mimura 2008). Similar cyclones in later years have resulted in fewer deaths in Bangladesh because of improved evacuation plans. However, countries such as Bangladesh more recently are experiencing different types of flood disasters, namely, floods from ever-rising sea levels because of global warming (Karim and Mimura 2008; Bhuiyan and Dutta 2012; Khan et al. 2011).

1.01.5.2 Tropical Cyclones

Hurricanes and hurricane surges are among the most devastating weather-related effects for coastal areas. The effects of a hurricane could cost billions of dollars in damage to local communities, and the death toll may possibly be overwhelming. Hurricanes usually form in late summer and early fall over warm tropical waters. They are a type of tropical cyclone (a low-pressure system forming in the tropics) with intense spiraling storm winds reaching speeds equal to or above 33 $\mathrm{m\ s^{-1}}$ (64 kt, 74 mph). There are several precursors to the formation of a hurricane: warm ocean waters (26.5 °C [80 °F]), humidity, weak vertical wind shear (shear is the movement of one layer of air over another), easterly waves (large areas of low-pressure air), convection, and thunderstorm activity. Hurricanes are fueled by the rise of warm humid air that later condenses to form clouds and rain. The heat, previously trapped in the water vapor, is released, and under the right conditions, a low-pressure system forms, causing wind to spiral inward (Lauber 1996). The devastating consequences of hurricanes could affect millions of residents, although the most vulnerable are the economically disadvantaged, such as elderly, children, pregnant women, parents, mentally ill, or those with preexisting medical conditions. An aftermath of a hurricane could be mortalities, permanent home displacement, injuries, poor hygiene, malnutrition, lack of access to safe water supplies, infections, scarce food sources, and psychological damages such as posttraumatic stress disorder (PTSD), posttraumatic stress symptoms (PTSS), major depressive disorders (MDD), or generalized anxiety disorder symptoms (GAD).

Hurricanes in the Atlantic have dramatically increased during the past decade and have caused more than $150 billion in damages in 2004 and 2005 (Pielke et al. 2008). The most costly and devastating hurricane to local residents was Hurricane Katrina that made landfall on the US Gulf Coast on 29 August 2005, destroying the city of New Orleans, LA, USA. The hurricane left behind immense damage, human fatalities, injuries, permanent home displacement, and mental distress to most of the local residents. In addition, the aftermath caused disruption in the supply of fresh water, insufficient access to safe food, direct exposure to environmental toxins, spread of infectious diseases, and lack of accessible medical care because of the destruction of infrastructure and medical centers. The death toll was estimated to be 1577 in Louisiana (Sharkey 2007), but the number is still a matter of controversy, because it is still unclear what was directly and indirectly affected by the hurricane.

The most vulnerable victims were pregnant women, children, elderly, low-income residents, and those with preexisting health conditions. Lack of information about preparedness, evacuation, and adequate transportation is a limiting factor for low-income families. A survey conducted at one of the shelters concluded that some of the residences never heard the evacuation order or did not understand the instructions; others who did hear the order did not have a car or other means for evacuation (Brodie et al. 2006). The same survey reported that 54% had no health insurance before the hurricane and 72% did not have insurance to cover their destroyed homes. In addition, 41% of the shelter residents did not evacuate because of preexisting health conditions, such as heart disease, hypertension, diabetes, or asthma. A large portion of the evacuees were low-income families with no health insurance, who relied on the New Orleans public hospital system for their medical needs before the hurricane, and this facility was destroyed in the storm (Brodie et al. 2006). Patients undergoing hemodialysis were also affected in the aftermath of the hurricane; 44.0% of participants in a study reported missing at least one hemodialysis session after the hurricane, and 16.8% reported missing three or more sessions (Anderson et al. 2009). Mental distress and PTSD were detected at high levels among residents of New Orleans and surrounding areas after the hurricane, compared to prehurricane levels. A study conducted of displaced groups 6–12 months post-Katrina and again 20–23 months later reported that mental distress levels did not decline between the two surveys (Abramson et al. 2008). Furthermore, traumas such as PTSD could leave long-lasting damages to those affected. A study assessing the effects of PTSD on young females (fourth to eighth grades) concluded that symptoms of PTSD not only persisted during the 2.5-year period but also increased with time (Weems et al. 2010). The psychological stress that was experienced during natural disasters reflects on also pregnant women with otherwise healthy pregnancies. Poor pregnancy in women with PTSD was observed in the aftermath of the Hurricane Katrina. For example, pregnant women exposed to the hurricane had low-birth-weight infants compared to those not exposed (Xiong et al. 2008).

Other effects of hurricanes, particularly to coastal inhabitants, are floods and the spread of infectious diseases. Such a scenario developed in 1998 when Hurricane Mitch hit Honduras, Guatemala, and Nicaragua and brought about 11 000 deaths. Acute respiratory infections (ARI) and acute diarrheas (AD) claimed a large portion of the lives (Campanella 1999). Comparison with predisaster data in Nicaragua showed that 6798 of 100 000 inhabitants were affected by AD compared to 2849 before the impact and that 1205 versus 295 of 100 000 inhabitants were affected by ARI (Campanella 1999). In addition, it was estimated that 58% of the 1998 maize crop and 6% of the bean crop were destroyed in the aftermath of Hurricane Mitch in Honduras (ECLAC 1999). These crops were the main source of income for many of the impacted residents. Furthermore, as a consequence of the floods after the hurricane, elevated levels of chlorinated and organophosphate pesticides were detected in adolescents (Balluz et al. 2001).

1.01.6 Extreme Wind Events

1.01.6.1 Dust Storms

Dust storms are one of the main contributors to a global rise of allergic reactions, asthma attacks, chronic breathing, lung problems, as well as cardiovascular and heart diseases. It has been estimated that the annual quantity of desert dust that makes regional or global airborne migrations is 0.5–5.0 billion tons (Perkins 2001). Dust storm refers to fine grain particles or sand dust picked up by strong wind forces and suspended in subsurface airflow for a long time. The event happens when wind forces surpass a given threshold level that acts on fine land particles, and as a result they are no longer held in the surface by their own weight and interparticle bonding (Squires 2007). Dust storms form mainly as a consequence of soil erosion by windstorms in drylands such as arid or semiarid regions, generally in subtropical latitudes.

Factors influencing the formation of dust storms include natural and anthropogenic forces. Extremely dry places throughout the globe, such as deserts, are the main cause of suspended dust in the air. Dust storms formed in the desert can travel long distances and affect areas that are not naturally arid, causing allergic reactions and asthma attacks in the local populations. Mattson and Nilsen (1996) point to the Sahara region in Africa as the main contributor of dust storms in the planet, affecting distant regions, such as Europe and the Americas, on a regular basis. Other arid places dispersing fine dust particles across oceans are the Sahel regions of North Africa and the Gobi and Takla Makan regions of Asia.

Dust storms from the Sahara are transported to the Americas over the Atlantic by tropical eastern winds. Some of the highest number of asthma casualties are in the Caribbean islands and are linked to African dust storms (Monteil et al. 2000). In the island of Barbados, for example, there has been a 17-fold increase of patients with asthma since 1973, which correlates with the onset of drought in Northern Africa in 1970 (Howitt 2000). Other symptoms recorded after dust events in the Caribbean islands include sinus stress, migraine headache, eye irritation, and chest pain. Another research demonstrates a link between concentrations of African dust and respiratory stress in the Caribbean island of Trinidad (Gyan et al. 2005).

Desertification caused by human activities and climate is another factor that opens new arid territories and grounds for the formation of dust storms. In China, for example, between 1975 and 1987, the desertification rate was approximately 2100 km^2 year^{-1} (Zhenda and Tao 1993). Many people suffer from sore throat and asthma after a dust storm in China. Owing to the low air quality and high concentration of pollutants in the air above China, dust storms are often mixed with heavy metals or airborne pathogenic microorganisms.

Severe drought in combination with poor land use is another factor that contributes to the formation of dust storms.

One of the most famous examples is the Dust Bow drought of 1930 in North America during which severe dust storms covered 75% of North America. The event began with the expansion of agricultural land during the 1920s. Much of the native drought-resistant grass in the Great Plains was replaced by wheat crops. With the onset of the drought in 1930s, much of the crop fields became devastated, exposing bare land to the forces of the wind (Cook et al. 2008, 2009). The dust storm reflected harshly on the health and socioeconomic state of the affected residents of the Plains. Many local people suffered what is known as 'dust pneumonia' – clogging of the lungs with dust, causing severe allergic reactions and the consequent death of thousands. The Dust Bowl also brought many people to poverty, lowering their health standards and forcing them to move to new areas leaving everything behind.

Dust storms are also transporters of microorganisms, some of which are highly pathogenic to humans. Microorganisms are natural inhabitants of top surface soils and sands and include bacteria, fungi, fungal spores, and viruses. During dust storms, they are easily picked up and carried along with the rest of the components in the storm (Griffin 2007). It is believed that dust particles cause abrasion to the nasopharyngeal mucosa in humans and thus promote microbial infections on inhalation (Molesworth et al. 2002). For example, outbreaks of meningitis due to *Neisseria meningitidis* infection are linked to dust storms that are common events during the dry season in North Africa (Sultan et al. 2005). In another research conducted in Mali, 25% of detected microorganisms during a dust storm were human pathogens (Kellogg et al. 2004). The fungal pathogen *Coccidioides immitis,* which causes coccidioidomycosis outbreaks, has been associated with dust storms. An outbreak of coccidioidomycosis was documented after a dust storm in a Naval Air Station in California (Williams et al. 1979).

1.01.6.2 Tornadoes

Tornadoes are natural disasters that are responsible for part of the world death toll each year. The enormous damage that tornadoes usually leave behind affects many aspects of the public health and economic stability of a region or a country. The most prevalent health impact that tornadoes cause are injuries from flying debris, fractures, head injuries, cervical spine trauma, psychological trauma, wound infections, lower hygiene due to home displacement, or outbreaks of infectious diseases. Tornadoes can form anywhere in the world and so far have been detected in every continent except Antarctica. However, the highest frequency of tornado incidences is in North America in the so-called Tornado Alley region of the United States. A tornado is defined as a violently rotating column of air extending from a thunderstorm to the surface of the Earth. The prerequisites for tornado formation are thunderstorm, moisture to feed thunderstorms, and temperature instabilities that are usually associated with spring and summer warming. Most tornadoes happen in agricultural areas where moisture is plentiful.

Tornadoes continue to cause loss of life in the United States (**Figure 2**), however, fatality rates have been well below 1:1 000 000 since 1975 (Brooks and Doswell 2002); despite this, there is a potential for considerable loss of property, subsistence, and life. While the 'Tornado Alley' region of North America has the highest tornado incidence, maximum of fatalities occur in the Deep South and this is likely due to differences in vulnerabilities of the areas' populations and perceptions of immediate danger (Ashley 2007).

The most immediate threat of tornadoes to humans is instant death. On average, the death toll varies from country to country and from year to year, but in general, densely populated areas prone to the formation of tornadoes, such as Bangladesh, have the highest mortality incidents (Finch 2008). Other threats such as injuries from flying debris are often associated with open wound infection. One such example was the outbreak among victims of unusual cutaneous mucormycosis or fatal necrotizing fungal soft-tissue infection due to mucormycete *Apophysomyces trapeziformis* several days after a tornado had struck Joplin, Missouri (USA) on 22 May 2011 (Center for Disease Control and Prevention 2011). This disease exhibits fatality rates between 29% and

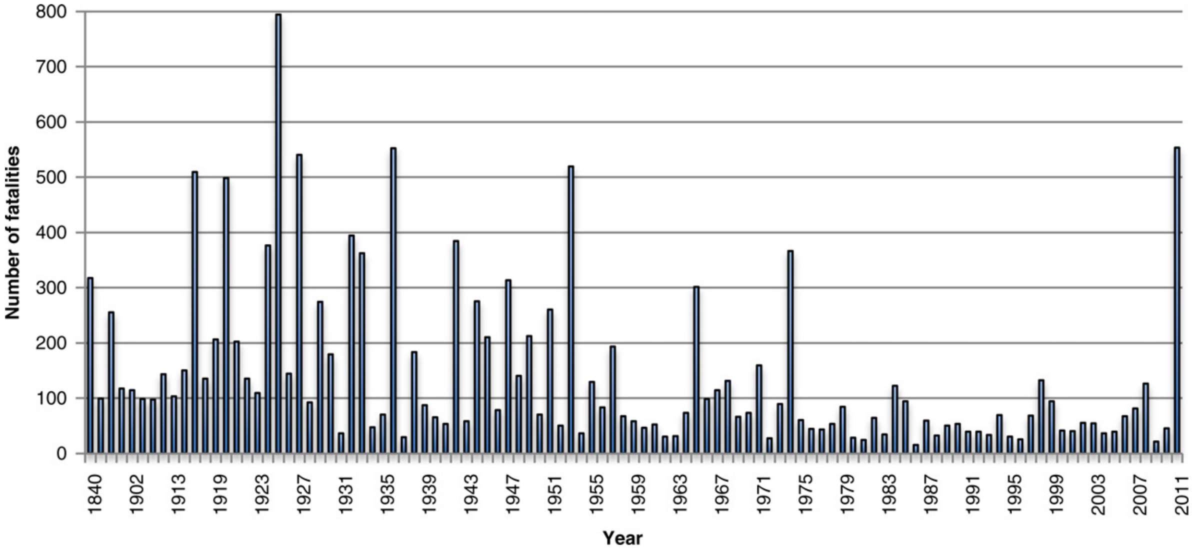

Figure 2 Fatalities attributed to tornadoes in the United States (1840–2011).

83% (Alvarez et al. 2010). Victims living through tornadoes can experience mental health-related complications or PTSD, which often affect them for life. The standard of life of such victims is immediately lowered because of their inability to return to work, or in the case of farmers, losing subsistence altogether.

Specific socioeconomic groups are extremely vulnerable to the aftereffects of tornado disasters. Among them are elderly, children, immigrants, those with preexisting health conditions, mentally ill, poor, or uneducated individuals. These groups are less likely to act adequately to an approaching disaster because of their limited access to receive and interpret forecasts or warnings. Poor groups are more likely to be affected by tornadoes disproportionately because of their economic disadvantage to purchase supplies, to secure better home structure, or to build a shelter. Mobile homes, often afforded by low-income groups, have light structures and frequently cannot withstand the wind forces associated with a tornado. It has been estimated that there is 10–15 times greater chance of fatalities due to tornadoes in mobile homes than there is in a permanent structure (Brooks and Doswell 2002; Simmons and Sutter 2006). For example, 43.2% (536 of 1240) of US tornado fatalities, between 1985 and 2007, occurred in mobile homes (Sutter and Simmons 2010). Sutter and Simons (2010) disclosed that less-powerful tornadoes on Enhanced Fujita Scale (EF1, EF2, or EF3) can bring just as much mobile home fatalities as the ones with a scale EF4 and EF5. Furthermore, the poor and less educated are less likely to have a reliable access to a warning system and thus less likely to comply in a timely manner. In addition, lack of reliable means of transportation before and after a disaster can exacerbate significantly the cause and effect of a tornado or hamper access to disaster assistance centers.

The disadvantage in an event of a tornado is often associated with a limited advance warning system. The elderly are greatly endangered because of that, since their impaired cognitive abilities and decreased sensory awareness to interpret warning systems limits their adequate response (Daley et al. 2005). They have been found to be the second most at-risk population after mobile home residents because of their compromised mobility and slower evacuation effort (Ablah et al. 2007). People with preexisting medical conditions, inside or outside medical facilities, are also extremely vulnerable to tornadoes, because their need for assistance could severely impact their effort for survival. Mental disorders too are likely to peak after tornados because of agitation, anxiety, and stress that affect survivors.

Hospitals are extremely vulnerable to the destructive forces of a tornado because many patients are dependent on medical equipment run by electricity. For example, one of the strongest tornadoes ever recorded in the United States occurred in Joplin, MO (on May 22, 2011) and devastated one of the city's major hospitals – St. John's Regional Medical Center. The hospital was left without power, and five people died during the night of the aftermath, despite the effort of the medical personnel to save their lives (SoRelle 2011). Hospitals are sometimes the only medical facility in some of the rural regions in United States, and if their structure and power are damaged by the indiscriminative path of a tornado, little help could be provided to the heavily injured or those already on hospital medical assistance.

Improved warning systems over the past 50 years have significantly decreased tornado-related fatalities. It has been estimated that the fatality rate dropped from 1.8 per million impacted residents to 0.11 per million (Sutter and Simmons 2010). Local, state, and federal educational programs can greatly reduce the number of fatalities attributed to tornadoes. The diverse levels of vulnerability and at-risk populations should be taken into consideration when educational approaches for disaster preparedness are being developed (Kusenbach et al. 2010). Different stressors should be applied when educational programs are being administered. For example, preparedness kits are often recommended to be kept in a sheltered area or a safe room. This does not apply to mobile home residents as they never should seek shelter in their own homes (Kusenbach et al. 2010). However, warning systems are ineffective if there is lack of underground disaster shelters or house basements. As it was the case in Joplin, MO, USA, nearly 78% of houses in the area lacked basements, owing to the area's rocky ground and high water table (Joplin Globe, 2011). One solution to that problem could be the construction of community shelters that could withstand the force winds associated with tornadoes. Other alternatives can include the construction of an in-house safe room with subsidies provided by FEMA or financial incentives from other public authorities.

1.01.7 Health Care Infrastructure and Emergency Preparedness

1.01.7.1 Risk Concepts – Risk Reduction and Management

Risk management is aimed at reducing losses to extreme weather-related disasters. As previously mentioned, developing countries are at a greater risk for negative effects of extreme weather events. Impoverishment and lack of local resources, governance, and infrastructure often contribute to a community's vulnerability. Natural disasters can reverse years and even decades of development work, and risk management needs to be implemented to reduce the vulnerability to these hazards. The first step in risk reduction and management is risk identification and assessment. While larger operatives, for example, government agencies, may assess risk based on predicted future scenarios, community risk assessment operates more at a local immediate level and is based on current coping capacities, from which extrapolations are made regarding future risk.

As discussed earlier, communities, countries, or regions differ greatly in vulnerability, and hence in the effects they may suffer from extreme weather events. Risk reduction will need to occur at various scales from educating a vulnerable population to global reduction of greenhouse gas emissions. It also will work at different political scales, from city governments to global networks such as the United Nations. Risk reduction will also need to involve a cross-sector multidisciplinary approach. Partnerships need to be developed between such different agencies as meteorological and health offices. On multinational, national, or regional scales, policies and regulatory measures must be developed and implemented to accomplish vulnerability reduction. For example, regulations controlling land use and housing structure quality can be enforced by public agencies. Development of infrastructure will play a large part in reducing vulnerability and ensuring development sustainability. While mitigating anthropogenic climate effects could result in far-reaching reductions of weather uncertainty and damage to natural resources and large-scale infrastructure, this top-down approach does not address differences in vulnerability to extreme weather events that typically operate at smaller scales.

Many climate extremes occur at smaller spatial scales, and so local authorities must have the building capacity to avoid the negative effects of these. The populace must be enabled to reduce risk at the individual and local level, giving individuals the knowledge, skills, and tools to reduce risk, for example, elderly people having the ability to prevent negative health effects of extreme temperatures via having access to home heating or cooling systems and the homeless having access to community shelters and appropriate clothing. Reduction of individual poverty and increasing livelihood success will enable communities to prepare for extreme weather events and to maintain (and preferably improve) current living standards despite any possible increase in frequency and intensity of extreme weather events.

Community-level action will be imperative in risk reduction at this scale. For example, land use planning and natural resource management, particularly watershed management, play a critical role in reducing risks of extreme weather events such as hurricanes and flooding. Economic losses due to Hurricane Mitch, which largely hit Central America in 1998, were more than $7.5 billion (USAID 1999). Much of these economic losses have been attributed to wide-scale deforestation, inadequate design, and ill-planned siting of housing and infrastructure (e.g., roads and bridges). Preserving forests conserves water resources and prevents flooding. By reducing runoff, forests control erosion and salinity. Consequently, maintaining forest cover can reduce siltation of rivers, protection of fisheries, and investment in hydroelectric power facilities (Chomitz and Kumari 1996). Areas with forest cover suffered fewer landslides than deforested areas, and terracing of deforested steep slopes aided in reducing landslides during extreme rainfall events of Hurricane Mitch (Sivanpillai and Thurow 2008). While Hurricane Mitch was the deadliest hurricane in the Americas since the 'The Great Hurricane' of 1780 and President of Honduras, Carlos Flores Facusse, claimed the storm destroyed 50 years of progress, it is certainly not an anomaly to the region (National Climate Data Center 1999). The Greater Caribbean Region experiences an average of 10 'named' tropical storms per year, of which 6 are classified as hurricanes; however, the activity is not uniform year to year, making predictions difficult (OAS 1991). Climate model scenarios suggest that the frequency and severity of extreme climate events might increase, although globally, tropical cyclone activity is at an all-time low (Maue 2012). For example, three of the last four Atlantic Basin hurricane seasons were exceptionally active. In the past 3 years, there were a total of 32 hurricane force tropical storms. This amounts to an average of eight per year, which is two above the long-term average of six storms a year (USAID 1999). Small underdeveloped nations in the Caribbean need to enable their residents to prepare for tropical storms to minimize their negative effects. There are examples where community-based programs aid greatly in adapting to extreme weather. A local NGO in Kitui, Kenya, has implemented a program to mitigate droughts by community building of 'sand dams,' which are designed such that water is stored in the sand that is kept behind the dam as an artificial aquifer (Lasage et al. 2006). Sand dams provide a close clean water source and have reduced walking distance, thereby increasing the time available for other productive activities.

Developing countries may be more vulnerable to the negative effects of extreme weather, but recent events show that developed countries are also at risk. For example, Typhoon Talas, which hit Japan in early September 2011, killed over 70 people, marking the deadliest tropical cyclone to affect the nation in 7 years. The recent (2011) droughts in Europe resulted in subsidence (affecting structure integrity), reduced crop production (leading not only to reduced food source but also to reduced livestock feed), and threats to power production (nuclear power reactors are water-cooled). Farmers were initially the hardest hit with loss of income because of reduced crop production, and many chose to sell livestock rather than feed them. Farming is inherently an uncertain business, and climate adds to this uncertainty and puts more pressure on this industry. Trickle-down effects included increased food prices, which affects low-income individuals and families the most. Building local food resilience will aid greatly in reducing vulnerability to effects of extreme weather events. People should be educated about and be involved in localized food production, farmers' markets, and gardening and farming projects in schools and by community groups to enhance food sustainability.

Recent floods in Australia highlight the fact that individual education and training are also imperative to preventing and coping with risks associated with extreme weather. In this case, it has been suggested that the dam operators made a suboptimal decision in assuming a no-rainfall scenario for dam discharge, resulting in downstream flooding (van den Honert and McAneney 2011). Challenges to an individualized approach, however, include difficulty in regulating this standardization and quality control maintenance. For example, it is difficult and resource intensive to test and maintain quality control of individual in-home health carers. Individualized approaches tend to be resource intensive and may pose problems when trying to implement these in large regions; however, they also tend to target the more vulnerable groups of a population and so have more of a positive impact.

1.01.7.2 Coping Capacity and Disaster Response

Society most often prepares for and responds to natural disasters using a top-down approach (e.g., national emergency relief institutions). Response decisions are made by governmental agencies, and vulnerable groups may be excluded from this process. Infrastructure designed to protect from such disasters is typically designed for the centers of urban areas. Vulnerable groups are often forced to live on the outskirts of urban areas, which subsequently puts them at higher risk to extreme events such as flooding. Advantages to a top-down approach include the availability of international funds, for example, when a country declares a state of emergency; this

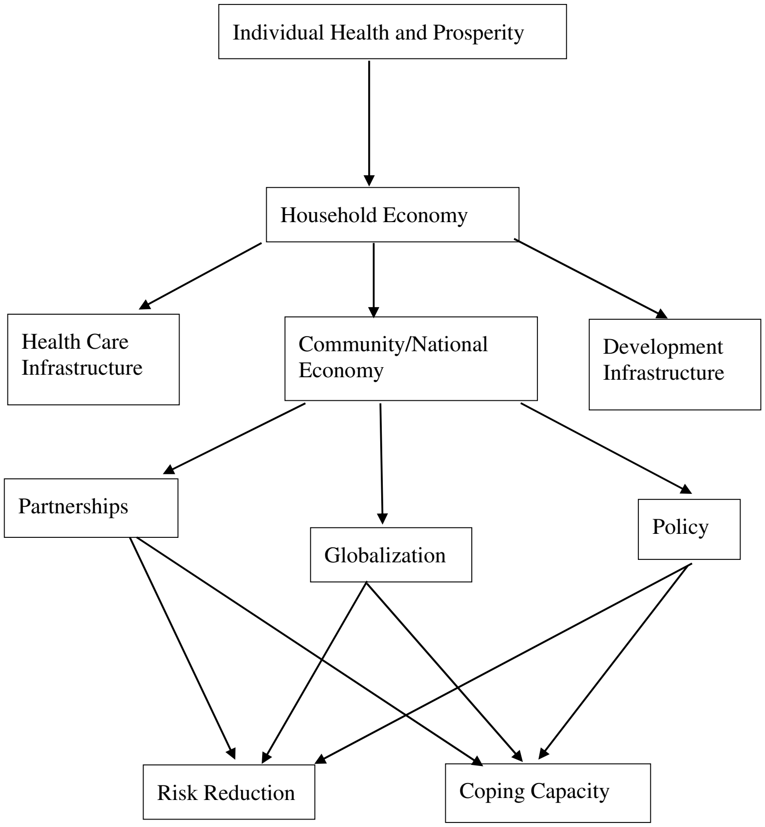
Individual Health and Prosperity
Household Economy
Health Care Infrastructure
Community/National Economy
Development Infrastructure
Partnerships
Globalization
Policy
Risk Reduction
Coping Capacity

Figure 3 Conceptual framework for a bottom-up approach to weather disaster risk management, reduction, and coping capacity.

shifts blame away from lack of preparedness and coping ability to the disaster itself (Schipper and Pelling 2006). However, a bottom-up approach, such as increasing social capital, enables preparedness, coping, and response at the individual and community level and works to equalize empowerment within the community. Social capital can be described as networks of relationships and flows of information within a society. Social capital concepts such as solidarity, social cohesion, social interaction, and social networks will enhance the capacity of individuals, groups, communities, and organizations to ensure social development and ability to cope with and respond to extreme weather events.

Self-help during disasters can be critical in an individual's ability to cope and survive. Health status affects an individual's ability to respond to and cope with disasters. There are gross inequalities in health between countries; for example, life expectancy at birth ranges from 34 years in Sierra Leone to 81.9 years in Japan (WHO 2004). However, there are also gross inequalities in health within countries. For example, in 2007, US county-level life expectancies ranged from 15 years ahead of the international frontier (average life expectancy in the top 10 countries) to over 50 years behind for men and 16 years ahead to over 50 years behind for women (Kulkarni 2011). Health disparities can be related to socioeconomic status and race/ethnicity; however, there are other factors that contribute, such as quality of care and education.

Many hospitals and other health care facilities, including long-term care facilities, operate 'at capacity' under normal daily conditions, and most are not prepared to meet a sudden increased demand for services resulting from an extreme weather event. Confounding this is the possibility that health care structures and services may be damaged or impaired directly as a result of the disaster and health care workers may be injured or killed. Indirect effects of extreme weather events on health systems include roads that may be damaged or compromised (e.g., blocked by debris or traffic of evacuees) limiting ambulance access to afflicted areas or flow of information to affected communities; gas may not be readily available to run ambulances. Adaptive capacity in the health sector is imperative in the ability to cope with and respond to such disasters and is reliant on individual health and prosperity (Figure 3).

Individual health and prosperity leads to higher public expenditure on health and improved human capital, for example, more local clinics and skilled health professionals. It also leads to competent and prepared local community groups, which enables resilience and ability to cope with disasters. Good disaster response management at the local level also maximizes available resources and distributes them within the community where they are most needed. The Red Cross often partners with community groups, such as church communities and community centers, and is often successful at working together and sharing resources to respond to disasters and rebuild afterward. The American Red Cross, working out of local churches and community centers, provided services for people with significant damage from the 2012 tornadoes in

Alabama, USA, meeting one-on-one with caseworkers and health and mental health professionals, offering local resources and referrals, help with prescriptions and other emergency medical needs, and bulk distribution of supplies such as tarps, rakes, shovels, trash bags, gloves, comfort kits of toiletry items and clean-up kits. Enabling local health professionals and citizens allows the community to work together to respond to and cope with extreme weather events, with the added benefit of building a stronger sense of community, which may in turn benefit the more vulnerable groups and individuals within.

1.01.8 Opportunities and Challenges for the Future

There lie ahead several far-reaching challenges to preparing for and coping with the uncertainty surrounding climate and extreme weather events. We have shown that many populations have survived extreme weather events. However, some sectors are more sensitive, and when affected, the gap between groups in their ability to cope and adapt can widen. Rather than blame for effects of disasters being placed on natural hazards, the main causes of disasters are due to human actions and the vulnerabilities of human beings. Focusing on the human aspect rather than the disaster itself will enable more effective risk management and disaster response.

Urbanization may not only lead to less poverty but also to increasing vulnerability due to development, for example, landslides, centralized water, and food supplies. However, rural areas that rely directly on agriculture and fisheries for food and livelihood can be devastated by even localized extreme weather events, and recovery can be lengthy. Increased communication technologies and partnerships will provide a solid framework for the development of risk mitigation and emergency response. Frameworks must be developed for mitigating risk and coping with disasters – linking the health sector to emergency planning groups.

Knowledge gaps exist, including a paucity of quantitative data on activities and health impacts of extreme weather events, on whether extreme weather events can be predicted, and on whether better warning systems can be put in place. There is a need for the characterization of relationships between extreme weather events and health outcomes, especially long-term and mental health effects. There is also a need to know what information is needed and how to communicate that information to the correct groups. Academic communities and policy makers must interact with each other and with groups educating disaster responders and communities to develop sustainable extreme weather event coping strategies and mechanisms to mitigate risk vulnerabilities.

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1.02 Recognizing and Reducing the Threats to Human Health and Environmental Ecosystems from Stratospheric Ozone Depletion

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1.02.1 Introduction

The anthropogenic generation of greenhouse gases and ozone-depleting substances has alternating, episodic effects on climate, stratospheric ozone loss, and human health. These effects are influenced by unpredictable natural cycles and extreme events, human resiliency and adaptive behaviors, and global economic and energy policy shifts. Such complex interrelationships affecting human health outcomes cannot be completely explained by predictive epidemiological or geospatial information system-based models and are better described using different paradigms that can account for the entire spectrum of environmental and sociobehavioral events that will occur in coming decades (Pielke et al. in press).

This chapter describes (1) the factors influencing ozone levels in the atmosphere, (2) the beneficial as well as the detrimental effects of ultraviolet (UV) radiation in man, and (3) the global warming potentials and ozone-depleting effects of the most commonly manufactured chlorofluorocarbon (CFC) substitutes in use today. In addition, the impact of UV radiation on marine and terrestrial food chains and ecosystem balance is addressed and supported by actual case studies in ozone layer thinning and excessive UV exposures in high-risk populations of humans and sentinel animals.

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1.02.2 Atmospheric Chemistry and the Ozone Cycle

Ozone is a toxic, water-soluble gas that is irritating to human mucous membranes and can induce upper airway hyperreactivity, precipitate bronchospasm, and aggravate asthma and other chronic lung diseases. Ozone is corrosive and can cause bleaching of painted surfaces, degradation of plastics, and discoloration and death of leafy vegetation (chlorotic mottling). Ozone is a photochemical pollutant and makes major contributions to urban smog, especially during summers and atmospheric inversions. Ozone is composed of three atoms of oxygen and is formed by tropospheric photochemical reactions in which UV radiation from the sun disassembles the oxygen atoms in atmospheric oxygen (O_2), in the oxides of nitrogen (NO_x), and in volatile organic chemicals (VOCs) and reorganizes these singlet oxygen atoms into triatomic ozone (O_3). The atmospheric reactions of the ozone formation cycle are depicted in Figure 1.

Although tropospheric ozone is toxic to man and a major atmospheric pollutant, stratospheric ozone protects life on Earth by absorbing the most harmful wavelengths of UV radiation from the sun. Stratospheric ozone is organized as a thin layer that spreads out between 10 and 50 km in the stratosphere, but is only 3 mm thick if compressed to ground level (Figure 2). The thickness of the stratospheric ozone layer is measured in Dobson units with 1 Dobson unit (DU) being equivalent to 0.01 mm of ozone thickness at standard temperature and pressure (0 °C, 1 atm) (Figure 2). The stratospheric ozone layer effectively absorbs all ultraviolet C (UV-C) and most of the damaging ultraviolet B (UV-B) radiation emitted from the sun in the bandwidths of 290–320 nm, but some UV-B and all higher bandwidth ultraviolet A (UV-A, 320–400 nm) still reach ground level with less photochemical activity, except for some cutaneous and ocular damaging effects.

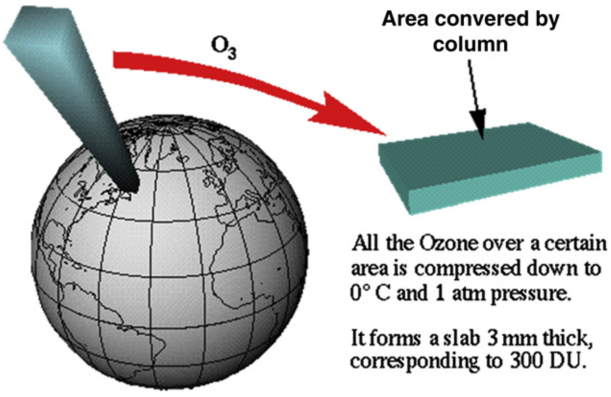
O_3
Area convered by column
All the Ozone over a certain area is compressed down to 0° C and 1 atm pressure.
It forms a slab 3 mm thick, corresponding to 300 DU.

Figure 2 Measuring the thickness of the stratospheric ozone layer in Dobson units using the Dobson spectrometer. One Dobson unit (DU) is defined as 0.01 mm of ozone thickness at standard temperature and pressure (STP = 0 °C and 1 atm). This figure shows a column of air over Labrador, Canada, which if compressed to STP will form a slab 3 mm thick or 300 DU. Source: US National Aeronautics and Space Administration (NASA), Goddard Space Flight Center. No copyright permission required. [Available online at http://toms.gsfc.nasa.gov/dobson.html.]

1.02.2.1 The History of Ozone Depletion

In 1974, Molina and Rowland, who later shared the 1995 Nobel Prize for their research in atmospheric chemistry,

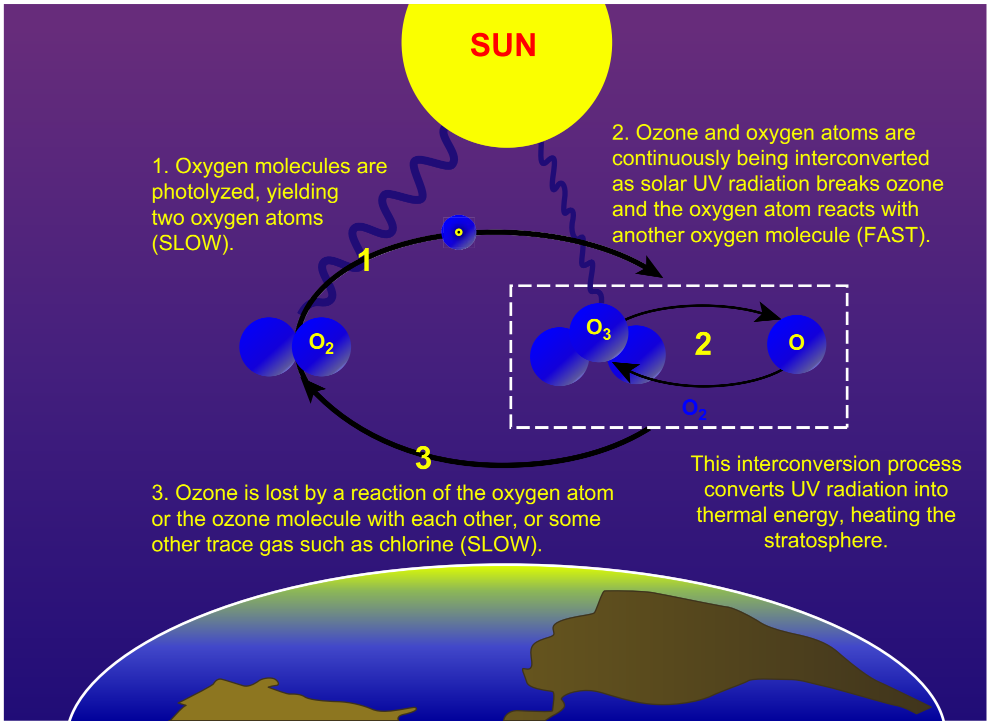
SUN
1. Oxygen molecules are photolyzed, yielding two oxygen atoms (SLOW).
2. Ozone and oxygen atoms are continuously being interconverted as solar UV radiation breaks ozone and the oxygen atom reacts with another oxygen molecule (FAST).
1
o
O_2
O_3
2
O
O_2
3
3. Ozone is lost by a reaction of the oxygen atom or the ozone molecule with each other, or some other trace gas such as chlorine (SLOW).
This interconversion process converts UV radiation into thermal energy, heating the stratosphere.

Figure 1 The atmospheric ozone cycle. Source: US Environmental Protection Agency. No copyright permission required. [Available online at http://www.epa.gov/ozone/science/process.html.]

proposed that UV-B protective stratospheric ozone was being destroyed by chemical reactions catalyzed by industrially produced chlorine- and bromine-containing hydrocarbons, particularly the CFCs (Molina and Rowland 1974). The CFCs were commonly used as refrigerants in air conditioning systems, as propellants in spray cans, and even metered dose inhalers (MDIs) for asthmatics (Molina and Rowland 1974). Although inert and environmentally stable in the troposphere, once the CFCs reached the stratosphere they were decomposed by high-energy UV radiation and released reactive chlorine atoms that severed the covalent bonds in ozone (O_3) releasing oxygen (O_2) and chlorine monoxide (ClO) (**Figure 1**) (Farman et al. 1985; NASA Earth Observatory 2011). A single chlorine atom could continue on this ozone-depleting pathway destroying over 100 000 molecules of ozone before becoming a less reactive compound precipitated out of the stratosphere by water vapor, such as hydrochloric acid (HCl) (NASA Earth Observatory 2011). The catalytic activity of chlorine atoms and, to a lesser extent, bromine atoms is responsible for the thinning and perforation of the ozone layer, especially in the polar, low-level ozone layers of the stratosphere (Farman et al. 1985; NASA Earth Observatory 2011). For every 1% decrease in the ozone layer thickness, the amount of UV-B exposure in the lower atmosphere, or troposphere, increases by approximately 2% (NASA Earth Observatory 2011). The average annual decrease in the thickness of the ozone layer in Dobson units is depicted in **Figure 3**.

1.02.2.2 The Ozone Hole

In 1985, Farman and coinvestigators discovered an unanticipated, irregular hole in the ozone layer over the Antarctic and urged the global community to seek CFC alternatives and a ban on CFC production (**Figure 4**) (Farman et al. 1985). Ozone holes developed over the polar regions, primarily over the Antarctic, as temperate region ozone layers thinned and fewer ozone molecules released less heat when absorbing the sun's UV-B rays. This resulted in a cooling of the stratosphere with more polar stratospheric cloud formation and greater generation of reactive chlorine molecules on the surface of ice crystals in the polar clouds.

The size and configuration of the ozone hole has been continuously measured by satellites since 17 September 1979, when the ozone level was 194 DU. From 1979 to 2003, all ozone hole measurements were made by US National Aeronautics and Space Administration's (NASA) Total Ozone Mapping Spectrometer (TOMS) instruments, and from 2003 to the present, the ozone hole has been monitored and measured by the Royal Netherlands Meteorological Institute (KNMI) (NASA Earth Observatory 2011). On 7 October 1989, the year that the Montreal Protocol on Substances that Deplete the Ozone Layer went into effect, the ozone level had dropped to 108 DU. On 9 October 2006, the ozone level measured 82 DU; but by 1 October 2010, the value was back up to 118 DU (NASA Earth Observatory 2011). The lowest value in the ozone layer, reflective of the deepest ozone hole, was measured on 30 September 1994, at 73 DU, while the largest

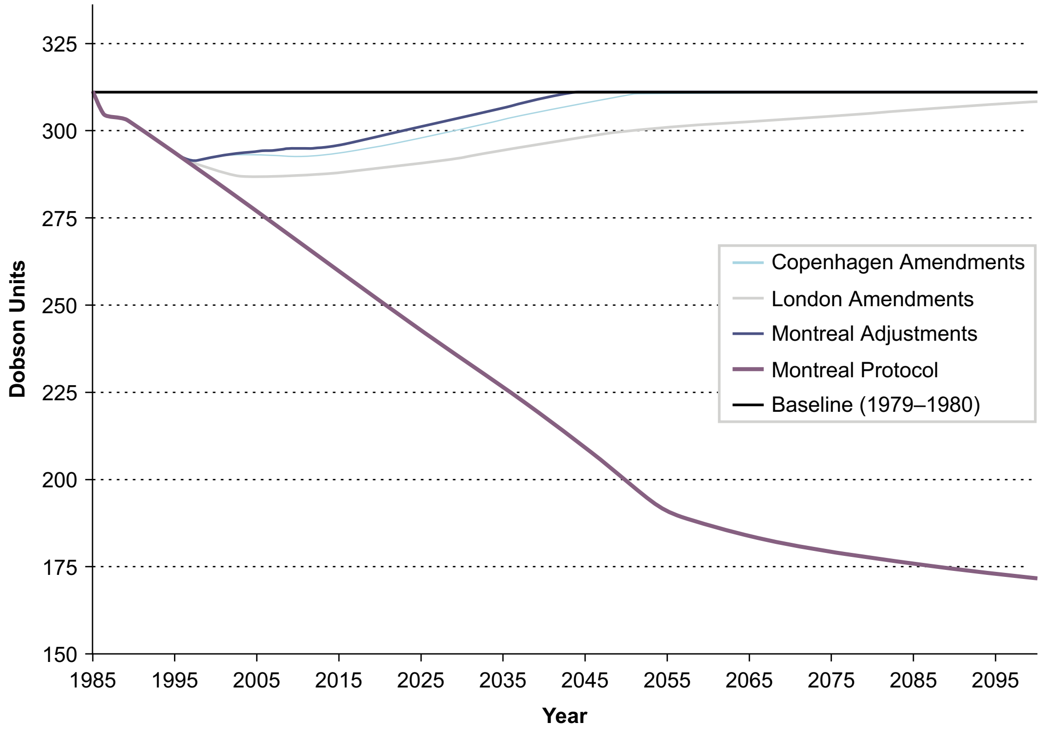

Figure 3 The average annual depletion in stratospheric ozone levels in Dobson units for the 30° N to 40° N degree latitude band in response to the Montreal Protocol and its subsequent Amendments. Source: Environmental Protection Agency (EPA), *Health Benefits of Stratospheric Ozone Protection: A Peer Reviewed Report*, 2006. No copyright permission required. [Available online at http://www.epa.gov/ozone/science/effects/AHEFApr2006.pdf.]

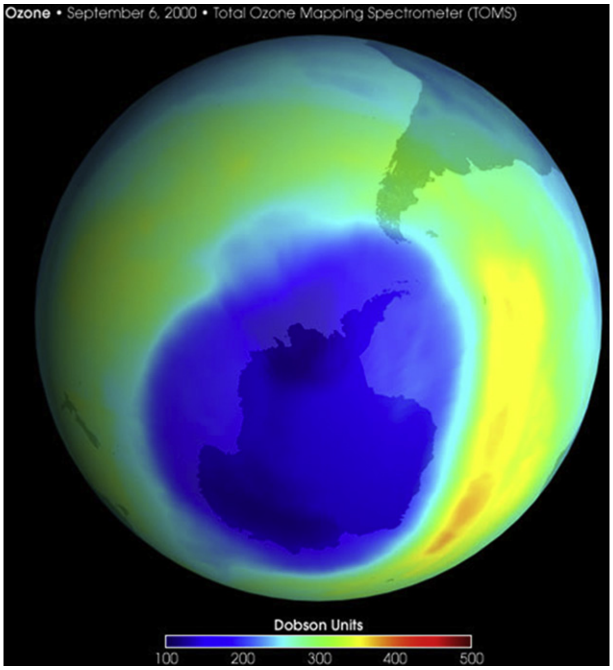
Ozone • September 6, 2000 • Total Ozone Mapping Spectrometer (TOMS)
Dobson Units
100
200
300
400
500

Figure 4 The largest hole ever observed in the stratospheric ozone layer opened over the Antarctic in September 2000, which covered 11.4 million square miles. Source: National Aeronautics and Space Administration (NASA). No copyright permission required. [Available online at http://earthobservatory.nasa.gov.]

ozone hole over the Antarctic occurred on 29 September 2000, when the ozone-depleted area stretched for 29.9 million square kilometers or 11.4 million square miles (Figure 4) (NASA Earth Observatory 2011). In 2010, the mean size of the ozone hole was 22.2 million square kilometers (NASA Earth Observatory 2011).

In addition to the human consequences of the Antarctic ozone hole, such as increases in sunburns and photosensitivity disorders, significant ecosystem consequences include melting of the Antarctic ice cap by increased UV radiation with rising sea and tidal levels and ocean surface overheating with reduced phytoplankton productivity in an important marine fishery (Abarca et al. 2002). Recently, a smaller, periodic ozone hole has been observed over the Arctic and was associated with increased UV-B radiation measured in Canada (NASA Earth Observatory 2011). Although ozone holes have been observed over the Antarctic and, to a lesser extent, over the Arctic, these changes in stratospheric ozone levels have occurred over primarily uninhabited areas of the world and not over areas of the world where the vast majority of people live.

1.02.2.3 Case Studies in Ozone Depletion I: Living under the Ozone Hole

In 2001, Abarca and coinvestigators published the results of their 15-year study on the incidence of sunburns and photosensitivity disorders treated by dermatologists in Punta Arenas, Chile, the southernmost large city in the world (population, 145 000), exposed to the Antarctic ozone hole every spring (Abarca et al. 2002). The authors reported a significant increase in the number of patients with severe sunburns during the austral spring of 1999 ($p < .01$), especially noticeable on weekends (29 of 31 cases) with significant ozone depletion days (<250 DU) and increased UV-B radiation (≥300 nm) (Abarca et al. 2002). Although not statistically significant, the incidence of photosensitivity disorders increased 51% over the last 7 years of the investigation (Abarca et al. 2002). The authors concluded that the incidence of serious sunburns increased during the spring of 1999 because of abrupt stratospheric ozone depletion with resulting increase in UV-B radiation at and above 300 nm, the most carcinogenic wavelengths, on days that Punta Arenas was under the Antarctic ozone hole (Abarca et al. 2002).

1.02.2.4 Other Environmental Factors Affecting Stratospheric Ozone Levels

The most significant factors responsible for ozone layer thinning and perforation are the industrial production and atmospheric disposal of halogenated hydrocarbons with the release of ozone-depleting reactive chlorine and bromine atoms. In addition, several other factors may influence stratospheric ozone concentrations including (1) stratospheric sulfate aerosols from volcanic eruptions, (2) stratospheric winds, (3) greenhouse gases, and (4) the increasing use of methyl bromide as an agricultural pesticide. Volcanic plumes can carry sulfur- and chlorine-containing aerosols high into the stratosphere and release more water vapor to form high clouds over the poles, generating more reactive chlorine molecules on ice crystals and further thinning ozone layers and widening the polar ozone holes. Stratospheric winds push the ozone layers around in a repeating cycle, the 26-month quasi-biennial oscillation (QBI), thinning some layers and thickening others. As greenhouse gases heat the troposphere and melt polar ice caps, ocean levels will rise, cooler winds will reduce air temperatures in the lower stratosphere, and more polar clouds will form with ice crystals that trap ozone-depleting chlorine and bromine molecules.

Methyl bromide is a colorless, odorless alkane gas that is used most often as an agricultural fumigant for agricultural commodities, grain elevators, mills, ships, greenhouses, and even furniture warehouses. It is highly effective against a wide range of pests including termites and most other insects, nematodes, rodents, fungi, and weeds. When methyl bromide is applied either as a gas fumigant or as a liquid, only a small amount is transformed into free bromide ions, and most of the volatile gas is released into the atmosphere. Methyl bromide was recognized as a major ozone-depleting substance by the Montreal Protocol and the US Clean Air Act, and its use was incrementally reduced in the United States and in other Montreal Protocol signee nations, until its complete phase-out from use on 1 January 2005. Nevertheless, methyl bromide has a long atmospheric half-life and remains in use as a gas fumigant under several allowable exemptions. In addition, methyl bromide gas is still used by non-UN member nations not participating in the Montreal Protocol and its subsequent amendments.

1.02.3 The Chronology of Stratospheric Ozone Depletion

Table 1 summarizes the chronology of stratospheric ozone depletion and the world's mitigation efforts to date beginning with the Montreal Protocol in 1987. The average annual depletion in stratospheric ozone levels in Dobson units for the 30° N to 40° N latitude band in response to the Montreal Protocol and its Amendments is depicted by the graph in Figure 3.

1.02.3.1 The Ozone-Depleting Chemicals

Although the CFCs were the first ozone-depleting substances to be manufactured and recognized as contributing to stratospheric ozone depletion, there are many other ozone-depleting chemicals that continue to be produced worldwide, including CFC substitutes. The major uses of the CFCs and CFC substitutes are depicted in Figure 5. The ozonedepleting chemicals are now identified by an international nomenclature that immediately identifies the substance as ozone depleting and concisely describes its chemical structure. The chlorine (or bromine) atoms in the chemical's structure make the chemical an ozone-depleting substance. All ozone-depleting chemicals and their substitutes are inert and environmentally stable in the atmosphere where they can remain for decades. Some of the ozone-depleting substances and their substitutes are summarized in Table 2. The lifetimes, total chlorine contributions, and global warming contributions relative to carbon dioxide of some selected ozone-depleting substances are summarized in Table 3.

1.02.3.2 Public Perception of Stratospheric Ozone Depletion

Public misperceptions about climate and stratospheric ozone depletion have a long history and continue to abound today. In 2010, Reynolds and coinvestigators reported the results of a study that compared the results of a 1992 survey on global warming and ozone depletion distributed to educated laypeople with the same survey administered to similar study subjects in 2009 (Reynolds et al. 2010). The investigators reported the following results (Reynolds et al. 2010): (1) In 1992, most respondents were unaware of the role of anthropogenic carbon dioxide emissions in global warming and often confused global climate change and stratospheric ozone depletion (Reynolds et al. 2010); (2) In 2009, most survey respondents showed higher awareness and comprehension of some climate change causes, identified energy use as a major cause of climate change, and rarely mentioned ozone depletion in the context of global warming (Reynolds et al. 2010). The authors concluded that many educated individuals still had incorrect beliefs about climate mechanisms and stratospheric ozone depletion (Reynolds et al. 2010).

Until 2000, ozone-depleting CFCs served as propellants for MDIs used by asthmatics and others with bronchospastic lung

Table 1 The chronology of stratospheric ozone depletion by chlorofluorocarbons (CFCs) and worldwide mitigation efforts

Year	*Ozone depletion recognition and mitigation efforts*
1913	Fabry and Buisson discover the ozone layer in the earth's atmosphere.
1928	Thomas Midgley, Jr., produces dichlorofluoromethane, the first CFC, later patented by DuPont as Freon®.
1930	General Motors and DuPont formed the Kinetic Chemical Company to mass produce Freon®.
1932	The Carrier Engineering Corporation used Freon® to produce the first self-contained home air conditioning unit, calling it an "Atmospheric Cabinet."
1935	Frigidaire and its competitors had sold eight million new refrigerators using Freon® in the United States.
1945–60s	One million metric tons of CFCs were sold annually for $1 billion (United States); air conditioning became affordable for homes, automobiles, and offices with Freon® as the preferred coolant in most systems; municipal public health codes were revised to designate Freon® as the only coolant that could be used in public buildings. CFCs were used in aerosol spray cans, paints, hair conditioners, and health care products.
1974	Molina and Rowland published the first study that confirmed that increase of chlorine levels from the breakdown of atmospheric CFCs significantly reduced the levels of stratospheric ozone.[a]
1975	Ramanathan published the first study that demonstrated greenhouse gas effect enhancement by CFCs augmenting increasing global surface temperatures from fossil fuel consumption.[b]
1978	US Environmental Protection Agency (EPA) bans CFCs in aerosol sprays in the Toxic Substance Control Act and Federal Food, Drug, and Cosmetic Act.
1985	Farman, Gardiner, and Shanklin published the first paper on the Antarctic ozone hole.[c]
1985	Vienna convention established a framework for 20 nations to share research and scientific assessment of ozone depletion, and to develop a protocol that would provide specific targets for CFC releases. No consensus was reached.
1987	Montreal Protocol signed by 43 nations. Participants agreed to freeze CFC production at 1986 levels and reduce production by 50% by 1999.
1990	Title VI of the US Clean Air Act directed the EPA to protect the ozone layer through regulatory and voluntary programs.
1995	Molina and Rowland received the Nobel Prize in Chemistry for their research in atmospheric chemistry.
1997	Kyoto Protocol to limit greenhouse gas emissions was adopted by many nations except the United States, China, and others.
2000	Largest single-day ozone hole over Antarctica covered 11.4 million square miles.
2006	Ozone hole reached prior record size, set a new record for lowest ozone concentrations and the deepest ozone hole observed.
2009	All 196 countries in the United Nations and the European Union ratified the original Montreal Protocol.
2011	Scientists detected a record of 40% depletion of Arctic ozone from winter to late March, breaking the prior record of 30%.

[a] *Molina, M. J., and F. S. Rowland, 1974: Stratospheric sink for chlorofluoromethanes: chlorine atom catalyzed destruction of ozone.* Nature, ***249***, *810–814.*

[b] *Ramanathan, V., 1975: Greenhouse effect due to chlorofluorocarbons: climatic implications.* Science, ***190***, *50–51.*

[c] *Farman, J. C., B. G. Gardiner, and J. D. Shanklin, 1985: Large losses of total ozone in Antarctica reveal seasonal ClO_x/NO_x interaction.* Nature, ***315***, *207–210.*

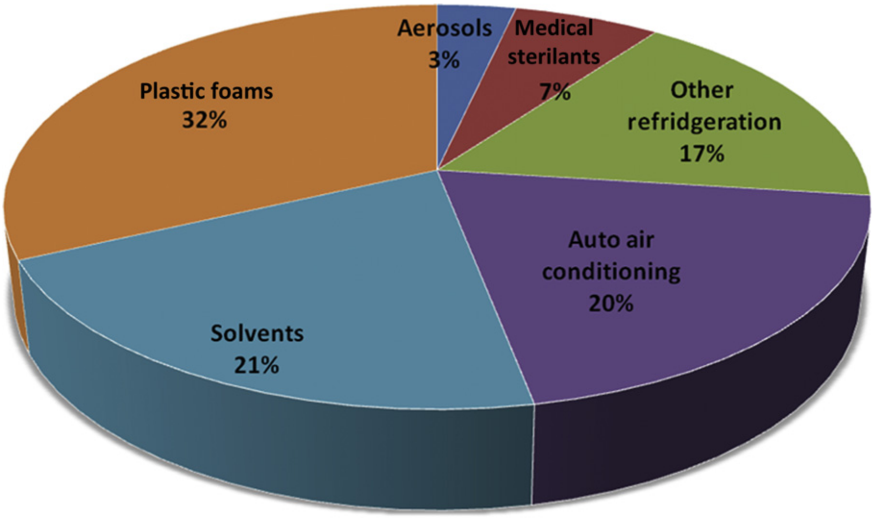

Figure 5 The major uses of chlorofluorocarbons (CFCs) and CFC substitutes. [Available online at http://www.epa.gov/sunwise/uvindex.html.]

Table 2 Some ozone-depleting substances and their substitutes

Prefix	*Meaning*	*Atoms in one molecule*	*Ozone-depleting substance or substitute*
CFCs	Chlorofluorocarbons	Cl, F, C	Depleting substance
HCFCs	Hydrochlorofluorocarbons	H, Cl, F, C	Depleting substance
HBFCs	Hydrobromofluorocarbons	H, Br, F, C	Depleting substance
Halon-Br, Cl	N/A	Br, Cl	Depleting substance
HFCs	Hydrofluorocarbons	H, F, C	Substitute
HCs	Hydrocarbons	H, C	Substitute
HFEs	Hydrofluoroethers	H, F	Substitute
PFCs	Perfluorocarbons	F, C	Substitute
Halon F, H	N/A	F, H	Substitute
Halon C	N/A	C	Substitute
HFAs	Hydrofluoroalkanes	H, F, C	Substitute

N/A, not applicable.

Table 3 The lifetimes, total chlorine, and potential global warming contributions of selected chlorinated and brominated fluorocarbons relative to carbon dioxide

Common names	*Chemical formulas*	*Lifetime (in years)*	*Total chlorine contributions (%)*	*Global warming contributions over 20 years (GWP units)*[a]
Carbon dioxide	CO_2	NA	0	1
CFC-11	CCl_3F	45	21	6730
CFC-12	CCl_2F_2	100	18	11 000
CFC-22	$CHClF_2$	12	1.6	5160
CFC-113	CCl_2FCClF_2	85	5	6540
Halon-1211	$CBrClF_2$	16	8	4750
Halon-1301	$CBrF_3$	65	3	8480
HFC-134a	CH_2FCF_3	14	0	3830

[a] *GWP units, global warming potential units. GWP is defined as the given mass of a chemical that contributes to global warming over a given period relative to carbon dioxide, which has a GWP of 1.0.*

conditions to relieve bronchospasm and improve breathing (Boulet 1998). The Montreal Protocol recognized the ozone-depleting properties of CFCs in MDIs and mandated a gradual phase-out of their use over the next decade as new non-CFC-containing MDIs were developed (Boulet 1998). In 1998, Liam and Lim reported the results of a survey study to assess the awareness of the ozone layer and its depletion by CFCs in MDIs among 113 consecutive asthmatic patients aged 12 years and older (Liam and Lim 1998). The investigators reported the following results (Liam and Lim 1998). (1) Although 65% of the patients were aware of the existence of the ozone layer, only 23% knew that CFCs played a major role in ozone depletion (Liam and Lim 1998). (2) Only 10% of the survey respondents knew that their MDIs used ozone-depleting CFCs as propellants (Liam and Lim 1998). (3) When informed of the role of CFC propellants in ozone depletion, 81% of 94 patients who preferred CFC-containing MDIs were willing to switch to multidose, dry powder inhalers once available on the market (Liam and Lim 1998). In summary, well-designed survey studies have now demonstrated that a majority of the lay public still do not understand the UV protective role of the ozone layer and the role of CFCs in ozone depletion.

1.02.3.3 The Time Line to Stratospheric Ozone Layer Restoration

Although atmospheric chlorine levels are decreasing, several factors will prolong the time line to restoration of pre-1980 thickness levels of the ozone layer, including rising bromine levels in many CFC substitutes, which continue to degrade ozone, and increasing volcanic eruptions with more halogen-trapping ice crystals in stratospheric clouds (Table 2) (McKenzie et al. 2003). Other factors that will prolong the time line to ozone layer restoration include the long half-life of phased-out CFCs and some of the ozone-depleting CFC substitutes and rising tropospheric ozone levels from photochemical effects on fossil fuel emissions (DeFabo 2005; Wilson et al. 2007; Tang et al. 2011). As tropospheric ozone levels increase and stratospheric ozone levels stabilize, there will be a change in the atmospheric chemistry of the boundary layer between the troposphere and the stratosphere with an increase in oxidation potential of the boundary layer, especially at the poles, which may allow other halogens, such as iodine, to enter the stratosphere and deplete ozone (DeFabo 2005; Wilson et al. 2007; Tang et al. 2011). Recent atmospheric modeling studies have suggested that elemental iodine, radioactive iodine from accidental nuclear power plant releases, such as occurred at the Fukushima Daiichi Nuclear Power Plant following an earthquake-generated tsunami in March 2011, and other iodine-containing substances from natural sources, such as the oceans, may increase stratospheric ozone depletion significantly in the polar regions during spring (Wilson et al. 2007).

1.02.4 Direct versus Indirect Human Health Effects of Ozone Depletion

The adverse health effects of stratospheric ozone depletion may be divided into direct and indirect health effects of increased UV-B radiation. The direct health effects of UV-B radiation include damage to target receptors in the skin, eyes, and cellular immune system. UV-B radiation damages DNA at neighboring pyrimidine sites and can cause mutations in p53 tumor suppressor genes precisely at these sites, resulting in squamous cell carcinomas (SCCs) (Brash et al. 1991; Ziegler et al. 1993). The risks of cutaneous SCCs increase with lifelong sun exposures, but basal cell carcinomas (BCCs) and melanomas appear to be more related to intermittent UV overexposures with severe sunburns in childhood than to prolonged exposures (Holman and Armstrong 1984). Skin cancers are the most common types of cancers, and the incidence of all three types of skin cancers is increasing with increasing UV-B radiation exposures (Brash et al. 1991).

Although the carcinogenic effects of UV-B radiation on the skin have been well studied, UV-B effects on the eyes are less certain, but animal and epidemiological investigations support association of cortical cataracts with excessive UV radiation (Dolin 1994). The incidence of cortical cataracts has now been predicted to rise by 0.5% for every 1% persistent decrease in stratospheric ozone, but such predictions will ultimately be confounded by UV-A and UV-B resistant glasses, aging of the world's population, and steroid-containing medication-induced cataract formation (Van der Leun et al. 1993).

The least well-studied adverse health effects of increased UV-B radiation are its effects on cellular immunity, which could result in increases in both malignant and infectious diseases (Van der Leun et al. 1993). As cellular immunity wanes with age and UV-B exposure, hematopoietic malignancies, such as non-Hodgkin's lymphoma, may increase, but such increases would be confounded most significantly by population aging and by technological advances in diagnostics and treatments (Van der Leun et al. 1993). Improvements in diagnostics will lead to more specific diagnoses (diagnostic biases), and as more effective treatments prolong the life of patients with hematopoietic malignancies, these diseases will become more prevalent (length-time biases). Increased UV-B exposures will likely cause greater severity of infectious diseases that have significant phases in the skin, such as herpes and infection by human papilloma viruses (HPVs) (Miura et al. 1994). Herpes labialis or "cold sores" on the lips triggered by sun exposures are frequent examples of local UV-B-induced immunosuppression with recrudescent infections (Miura et al. 1994).

The indirect health effects of UV-B radiation are caused by the impact of increased UV-B irradiation on the environment and include greater tropospheric contributions to photochemical smog, with aggravation of chronic respiratory diseases, such as asthma and chronic obstructive pulmonary disease (COPD) (Van der Leun et al. 1993). More dramatic indirect effects of ozone depletion and increased UV-B radiation could stem from diminished world food production as a result of UV-B effects on agricultural crops and marine fisheries.

1.02.4.1 Are There any Beneficial Human Health Effects from Ultraviolet Radiation?

The most significant beneficial health effect of limited daily exposure to UV-B radiation is the photochemically driven production of vitamin D_3 from 7-dehydrocholesterol in the skin, which is then converted to its active metabolite, 1, 25-dihydroxy vitamin D (Rhodes et al. 2010; Holick et al. 1982). Vitamin D is essential for bone health, especially in estrogen-deficient and postmenopausal women, but any deficiencies in vitamin D from reduced UV-B exposures could be easily tempered by vitamin supplements and vitamin D-fortified foods, such as bread and milk. In addition, the production of biologically active vitamin D in the skin is self-limiting and controlled by a feedback loop mechanism that maintains constant levels (Holick et al. 1982). In a 2010 study designed to measure the amount of time spent in summer sunlight to maintain sufficient vitamin D levels ($\geq 20\ \text{ng ml}^{-1}$) in humans, Rhodes and colleagues exposed 120 British Caucasians wearing T-shirts and shorts to simulated summer's sunlight exposures in Manchester, United Kingdom (53.5° N), and determined that 13 min of summer sunlight exposures to 35% of skin surface areas would produce sufficient ($\geq$20 ng ml^{-1}) but not optimal levels ($\geq$32 ng ml^{-1}) of vitamin D_3 at UK latitudes (Rhodes et al. 2010).

Although there is conclusive evidence to support the critical role of vitamin D in bone metabolism, there is much less conclusive evidence to support its role as being protective against internal cancers, such as colorectal cancer, and chronic neurological diseases, such as multiple sclerosis (Holick et al. 1982). Multiple sclerosis is indeed more prevalent at higher latitudes with less UV radiation and more vitamin D insufficiency (Norval et al. 2011). However, such an association is confounded by postinfectious autoimmune activity stimulated by more frequent viral infections in higher latitudes with colder climates, family history of chronic demyelinating diseases, and vitamin D supplementation.

1.02.4.2 Measuring Human Exposures to Ultraviolet Radiation: The UV Index

The UV index was initially introduced in Canada in 1992 in response to growing concerns about increasing human exposures to excessive UV radiation due to stratospheric ozone depletion (Fiolitov et al. 2010). In 1994, the UV index was adopted as the standard indicator of UV levels by both the World Meteorological Association and the World Health Organization (WHO) (Fiolitov et al. 2010). The UV index is a daily calculated measure of the strength of solar UV radiation projected on a national map and reflected on a multicolor, visual analog scale from a low exposure level of 1 to an extremely high exposure level of 11+ (Figure 6) (Norval et al. 2011). UV index values can be calculated from satellite measurements of cloud cover and stratospheric ozone using radiation transfer models or measured by ground-based spectrometers, broadband filter radiometers, or multifilter radiometers (Fiolitov et al. 2010). Over the United States and Canada, mean noontime UV index values in summer will range from 1.5 in the Arctic to over 11+ in Texas and Hawaii (Figure 6) (Fiolitov et al. 2010). Several other temporal and physical factors can affect the UV index in addition to ozone levels and cloud cover and include time of the day, season of the year, sun angle of elevation, altitude, latitude, air pollution, rain, and snowfall (Fiolitov et al. 2010). In the United States, the National Weather Service calculates the predicted UV index for the next day in every region and posts its results on the US Environmental Protection Agency (EPA) website (http://www.epa.gov/sunwise/uvindex.html), where individuals may register to receive personal e-mail notifications of high-UV alerts in order to take precautions from excessive UV exposures outdoors (Table 4).

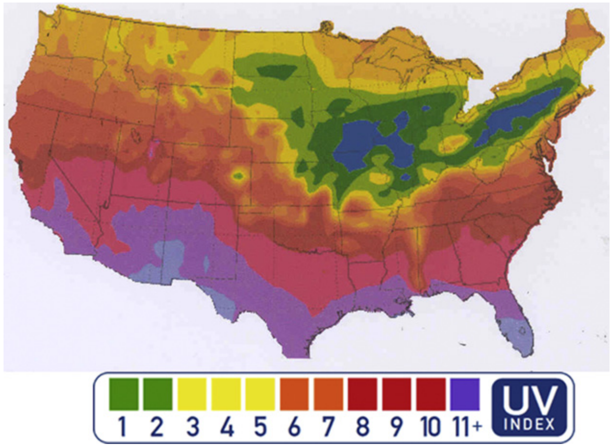

Figure 6 The daily (29 August 2011) UV index forecast map of the United States and color legend. Source: US Environmental Protection Agency. No copyright permission required. [Available online at http://www.epa.gov/sunwise/uvindex.html.]

1.02.4.3 Cutaneous Effects of Excessive Ultraviolet Radiation

The uncovered skin is exposed to UV radiation outdoors, receives the largest doses of UV radiation, and suffers the most significant adverse effects, including photoaging, sun allergy, premalignant skin lesions (actinic keratoses (AK)), and skin cancers of which the most common types are classified as nonmelanoma skin cancers (NMSCs; BCC and SCC) and cutaneous malignant melanoma (CMM) (Narayanan et al. 2010). Skin cancers exhibit different sun exposure-related risk factors with early, intermittent overexposures and blistering sunburns associated with BCC and CMM, and chronic and cumulative overexposures associated with SCC (Rittié et al. 2007; Diepgen and Mahler 2002; World Health Organization 2011; Preston and Stern 1992).

1.02.4.3.1 Nonmelanoma Skin Cancers

The nonmelanoma skin cancers (NMSCs) include BCC and SCC, comprise 95% of all skin cancers, and are the most commonly occurring malignancies among fair-skinned populations worldwide (Narayanan et al. 2010; Diepgen and Mahler 2002; World Health Organization 2011). The world incidence of NMSCs is estimated to be 2–3 million cases each year (Narayanan et al. 2010; Rittié et al. 2007; Diepgen and Mahler 2002; World Health Organization 2011; Preston and Stern 1992). An upward trend in NMSCs has now been observed in Australia, Europe, and the United States, with an average annual increase between 3 and 8% (Diepgen and Mahler 2002; World Health Organization 2011; Preston and Stern 1992).

Dark-skin populations are protected from UV radiation by increased levels of epicutaneous melanin and have significantly lower annual incidence rates of NMSCs (Gloster and Neal 2006). Epicutaneous melanin in Blacks filters twice as much UV-B radiation as does that in Whites (Gloster and Neal 2006). The epidermis in Blacks transmits 7.4% of UV-B and 17.5% of UV-A rays, compared with 24 and 55% in Whites, respectively (Gloster and Neal 2006).

BCC now accounts for 80–85% of all NMSCs and is the most common malignancy in Whites (Diepgen and Mahler 2002; World Health Organization 2011; Preston and Stern 1992). BCC is the most commonly diagnosed cancer in the United States and now accounts for approximately 30% of all cancer diagnoses (World Health Organization 2011). The annual worldwide incidence rate of BCC is increasing by nearly 10%, with the highest rates in elderly men (Diepgen and Mahler 2002; World Health Organization 2011). Although BCCs may occur anywhere on the body; they usually occur as

Table 4 Interpreting the US Environmental Protection Agency's daily UV index map

UV index number	*Index map color code*	*UV exposure category*	*Recommended exposure protection*
1-2	Green	Low	Sunglasses, sunscreens 15+
3-5	Yellow	Moderate	Hat, sunglasses, sunscreens 15+
6-7	Orange	High	Hat, sunglasses, sunscreens 15+, long-sleeved shirt and long pants, avoid midday exposures
8-10	Red	Very high	Hat, sunglasses, consider sunscreens 30+, long-sleeved shirt and long pants, avoid exposures from 10 a.m to 4 p.m., bright surfaces (sand, snow, water) reflect and double uv exposures
11+	Purple	Extreme	Hat, sunglasses, sunscreens 30+, long-sleeved shirt and long pants, avoid exposures from 10 a.m to 4 p.m., bright surfaces (sand, snow, water) reflect and double uv exposures

nonhealing ulcers or papulonodules on sun-exposed areas, especially on the head (nose, ears) and neck, and rarely metastasize (Figure 7) (Rittié et al. 2007; Diepgen and Mahler 2002; World Health Organization 2011; Preston and Stern 1992). The most significant risk factors for BCCs are repeated overexposures to UV-B irradiation, even without sunburns, in childhood and as young adults. Although BCCs develop slowly and rarely metastasize to other organs, they can be locally and deeply invasive, very disfiguring, and place significant financial and utilization burdens on health care systems worldwide (Rittié et al. 2007; Diepgen and Mahler 2002; World Health Organization 2011; Preston and Stern 1992).

SCCs begin in the uppermost layer of the skin, account for approximately 15% of all skin cancers, and have a 10-fold greater risk for metastasis and death than BCCs (Narayanan et al. 2010; Rittié et al. 2007; Diepgen and Mahler 2002; World Health Organization 2011; Preston and Stern 1992). Both BCCs and SCCs arise from keratinocytes in the epidermis, the former probably from a pleuripotential stem cell. SCCs usually occur in sun-exposed areas of the head (ears), face (nose, lips, and eyelids), neck, and hands and may be heralded by premalignant AK, rough and scaly pink patches (Figure 8) (Narayanan et al. 2010; Rittié et al. 2007; Diepgen and Mahler 2002; World

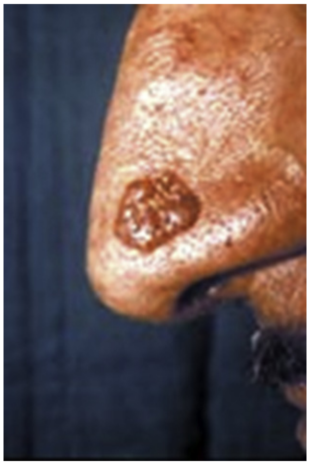

Figure 7 Ultraviolet radiation-induced basal cell carcinoma on the left side of the nose. Basal cell skin cancers erode tissue locally, can be quite disfiguring, and do not usually spread or metastasize distantly to other organs. Source: US Centers for Disease Control and Prevention (CDC). No copyright permission required. [Available online at http://www.cdc.gov/excite/skincancer/mod10.thm.]

Health Organization 2011; Preston and Stern 1992). Smokers, roofers, and asphalt road workers are exposed to combinations of aerosolized carcinogenic polycyclic aromatic hydrocarbons and UV radiation and are predisposed to SCCs in sun-exposed areas, such as the face, arms, and hands (Table 5) (Narayanan et al. 2010; Rittié et al. 2007; Diepgen and Mahler 2002; World Health Organization 2011; Preston and Stern 1992). In women, both BCCs and SCCs occur more commonly on the legs than in men as a result of greater sun exposures at these sites (Diepgen and Mahler 2002).

The most commonly used measure to gauge the potential increase in NMSC incidence rates related to ozone depletion and increased UV-B exposure is the amplification factor (AF) (Rubenstein et al. 1999). The AF is the percentage increase in NMSCs that would result from a 1% decrease in stratospheric ozone (Rubenstein et al. 1999). The AFs for BCC and SCC are 1.7 and 3.0, respectively (Rubenstein et al. 1999). Therefore, for each 1% sustained decrease in stratospheric ozone, the annual incidence rates for BCCs and SCCs in fair-skinned persons will

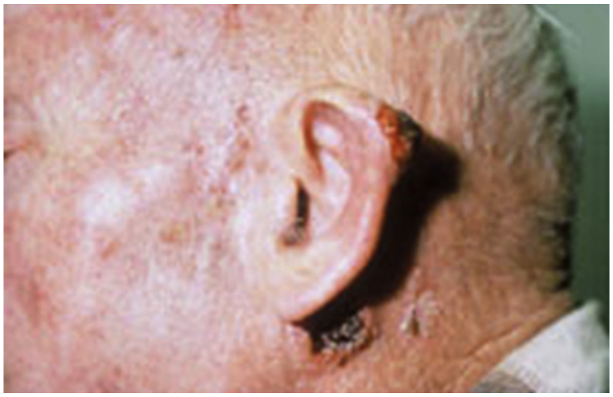

Figure 8 Ultraviolet radiation-induced squamous cell carcinoma on the left ear and mastoid process. Squamous cell skin cancers erode tissue locally, can be quite disfiguring, and can spread or metastasize distantly to other organs. Source: US Centers for Disease Control and Prevention (CDC) No copyright permission required. [Available online at http://www.cdc.gov/excite/skincancer/mod10.thm.]

Table 5 Risk factors and prevention strategies for skin cancer

Risk factors for skin cancer	*Prevention strategies for skin cancer*
UV radiation exposure	**Minimize sun exposure**
UV-A	Especially during peak sun hours, 10 a.m. to 4 p.m.
UV-B	
Immunosuppression	**Sun protection**
UV radiation	UV-A and UV-B resistant wrap-around sunglasses
Acquired immunodeficiency syndrome (AIDS)	Sun protective clothing with tightly woven fabric
Immunosuppressive therapy	Wide-brim hat
Organ transplant antirejection therapy	
Genetic syndromes	**Sunscreens**
Basal cell nevus syndrome	Sunscreen with high SPF, ≥15
Epidermodysplasia verruciformis	Apply sunscreen to children ≥6 months of age
Oculocutaneous albinism	Reapply sunscreen every 2 h while outdoors, even on non-sunny days
Xeroderma pigmentosum	
Clinical therapies	**Avoid artificial tanning (beds and booths)**
Phototherapy	
Psoralen + UV-A therapy (PUV-A)	
Viruses and infections	**Sun safety education**
Human immunodeficiency virus	Age-appropriate public health education
Human papilloma virus	Directed skin cancer education: families, coaches, teachers, administrators, primary care physicians
Environmental pollutants and chemical carcinogens	**Screening**
Arsenic	Periodic free screening programs
Chromium	
Polycyclic aromatic hydrocarbons	
Ionizing radiation	**Skin examinations**
X-rays	Mole watch
	Frequent self-screen examinations
	Skin examinations by dermatologists
Miscellaneous risk factors	**Policies, services, and organizations**
Advancing age	Promotion of health services and organizations that support skin cancer education
Alcohol intake	Planning and implementation of national public health policies that reduce UV exposures in populations
Artificial tanning	
Dermatoses and keratoses	
Fair skin color	
Nonhealing wounds and scars	
Outdoor occupations	

increase by 1.7 and 3.0%, respectively (Rubenstein et al. 1999). The combination of the increased carcinogenic potential of UV-B at 300 nm and the UV-B absorption spectrum for stratospheric ozone would result in a calculated AF of 1.6% or a 10% decrease in ozone (Rubenstein et al. 1999). If sustained, this level of ozone depletion would increase the annual incidence of BCCs by 30% and SCCs by 50% among fair-skinned persons worldwide (Rubenstein et al. 1999).

1.02.4.3.2 Cutaneous Malignant Melanoma

Cutaneous malignant melanoma (CMM) accounts for approximately 5% of skin cancers worldwide and has the highest case fatality rates (World Health Organization 2011). CMM is now the most commonly increasing malignant disease, with an estimated annual incidence rate increase of 3–7% (World Health Organization 2011). The WHO has estimated that 132 000 new cases of melanoma will occur each year worldwide (World Health Organization 2011). In the United States, melanomas comprise 3–5% of skin cancers, but account for approximately 75% of skin cancer deaths (Holman and Armstrong 1984). In 2010, an estimated 68 130 people in the United States were diagnosed with melanoma, and an estimated 8700 patients died, according to the US National Cancer Institute. Annual melanoma incidence rates in the United States are 16 times greater in Whites than African–Americans and 10 times greater in Whites than in Hispanics (Holman and Armstrong 1984; Narayanan et al. 2010). About 1 in 50 people in the United States will be diagnosed with melanoma at some point in their lives (Holman and Armstrong 1984; Narayanan et al. 2010).

Melanomas begin in melanocytes, are usually darkly pigmented, and occur more commonly on the trunk in men and on the legs in women (Figure 9) (Diepgen and Mahler 2002). Melanomas are more common in fair-skinned people with light-colored eyes (blue, green) and blond or red hair (Diepgen and Mahler 2002). The characteristic physical features of melanomas, often described as the ABCDs of melanomas, include (1) asymmetric shape, (2) border irregularity, (3) combination of colors, and (4) diameters larger than a pencil eraser (6 mm) (Figure 9). Besides ethnicity and family history, the greatest risk factors for melanomas include three or more blistering sunburns before age 18–20 years, congenital nevi (moles), large numbers of moles, and long-term phototherapy with psoralens and UV-A (PUV-A) (Table 5). Although an association between UV-B overexposures and NMSCs has been well established, the relationship between UV-A exposure and melanoma is not as clear, but supported by several observations including the greater carcinogenicity of low-bandwidth UV-A in PUV-A therapy as a risk factor for both NMSCs and melanomas (Diepgen and Mahler 2002; Salmon et al. 2007).

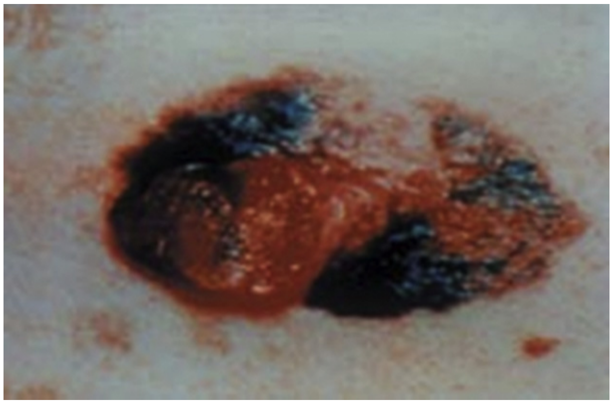

Figure 9 Ultraviolet radiation-associated malignant melanoma. Note the asymmetric and irregular border and the multiple color shades. Malignant melanomas must be managed with early and aggressive surgical excision and will frequently spread or metastasize distantly to other organs. Source: US Centers for Disease Control and Prevention (CDC). No copyright permission required. [Available online at http://www.cdc.gov/excite/skincancer/mod10.thm.]

1.02.4.4 Case Studies in Ozone Depletion II: Cutaneous Malignant Melanomas in New Zealand

In the United States, CMM is the sixth most common cancer in males and the seventh most common cancer in females per capita, but in Australia and New Zealand, melanoma is the fourth most common cancer in males and the third most common cancer in females per capita (Salmon et al. 2007). Although the incidence rates for melanoma were comparable in Queensland, Australia, and New Zealand throughout the 1980s, melanoma incidence rates in New Zealand have now surpassed incidence rates in neighboring Australia and have become the highest incidence rates for melanoma in the world, especially in the Tauranga region of New Zealand (Salmon et al. 2007).

In order to determine the incidence of melanoma in the Tauranga region (Tauranga and Western Bay of Plenty Regions, North Island of New Zealand), Salmon and coinvestigators reviewed all histopathological reports of both in situ and invasive melanomas in the region reported during 2003 and compared the age-standardized incidence rates for the Tauranga region stratified by the entire population and non-Maori population with incidence rates in Australia and the Northern Hemisphere (Salmon et al. 2007). The age-standardized incidence of invasive melanoma in the non-Maori population was 79/100 000, and the age-standardized rate for the entire population was 70/100 000 (Salmon et al. 2007). The rate of in situ melanoma was 78/100 000 for the non-Maori population and 72/100 000 for the entire population (Salmon et al. 2007). The investigators attributed the exceptionally high incidence of melanomas in Tauranga, New Zealand, to the higher levels of UV irradiation in areas of the Southern Hemisphere under the ozone hole and to the relatively cool summer temperatures of the region, which encouraged outdoor exposures, especially among the fair-skinned population of the region (Salmon et al. 2007).

1.02.4.5 Ocular Effects of Excessive Ultraviolet Radiation

Although UV radiation is a recognized risk factor for conjunctival pterygia and cortical cataracts, the scientific evidence to support an association between UV exposure and retinal malignant melanoma and age-related macular degeneration of the retina is not as powerful. The ocular effects of acute and chronic UV-B on the eyes and eyelids are summarized in Table 6 (Jones 1992; Norval et al. 2007; Schein et al. 1995). Besides excessive solar UV exposure, other well-known risk factors for conjunctival pterygia include male gender, outdoor occupation or avocation, and proximity to the equator (Figure 10).

Table 6 The acute and chronic effects of UV-B exposure on the eyes and eyelids

Ocular structures	*Acute UV-B effects*	*Chronic UV-B effects*
Eyelids	Sunburn Blistering Exfoliation Hyperpigmentation	Freckling Lentigines (age spots) Hypomelanosis (vitiligo) Actinic keratosis Nonmelanoma skin cancers (BCC, SCC) Malignant melanoma Drug-induced photosensitivity
Conjunctiva	Chemosis (swelling) Photoconjunctivitis Reactivation of herpes simplex keratoconjunctivitis	Dyskeratosis Intraepithelial neoplasia Pinguecula
Cornea	Photokeratitis Endothelial damage Reactivation of herpes zoster ophthalmicus	Climatic droplet keratopathy Endothelial changes Pterygium
Lens	Anterior subscapular opacities	Cortical cataract
Retina	Not applicable presently	Potentially retinal malignant melanoma and aggravation of age-related macular degeneration

BCC, basal cell carcinoma; SCC, squamous cell carcinoma.

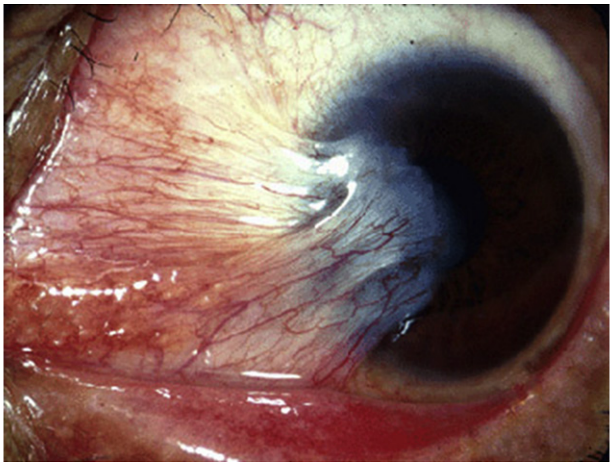

Figure 10 Conjunctival pterygium. The well-known risk factors for conjunctival pterygia include male gender, outdoor occupation or avocation, proximity to the equator, and excessive solar UV exposure. Source: Wikimedia Commons, a freely licensed media file repository. Attribution: Jonathan Trobe, M.D., University of Michigan Kellogg Eye Center, posted 16 August 2011. [Available online at http://www.kellogg.umich.edu/theeyeshaveit/red-eye/pterygium.html and http://en.wikipedia.org.wiki/File:Pterygium_(From_Michigan_Uni_site_CC_BY).jpg.]

1.02.4.6 Immune System Effects of Excessive Ultraviolet Radiation

UV-induced immunosuppression can act both locally and systemically to adversely affect the skin's immune systems as the first barriers against viral skin infections and carcinogenesis by the following mechanisms: (1) diminishing antigen-presenting cell functions, (2) inducing production of immunosuppressive cytokines, (3) modulating contact and delayed-type hypersensitivity reactions, and (4) suppressing cell-mediated immunity (Narayanan et al. 2010). UV-induced immunosuppression contributes to the progression of both melanoma and NMSC by causing DNA damage, interfering with DNA repair, and inhibiting p53 tumor suppression genes (Narayanan et al. 2010; Rittié et al. 2007). Nevertheless, the exact mechanisms of UV-induced immunosuppression and its relationships to the induction of skin cancers have not been fully elucidated.

Epidemiological investigations have now supported associations between UV exposures and NMSCs in immunosuppressed transplant recipients, between UV exposures and reactivations of cutaneous herpes simplex viral (HSV) infections, and between UV exposures and HPV-associated infections and NMSCs (Ichihashi et al. 2004; Akgul et al. 2006). Renal transplant recipients taking immunosuppressive therapies are more susceptible to skin cancers, 90% being NMSCs, if they are light skinned and have frequent UV-B exposures (Terhorst et al. 2009).

1.02.4.7 Special Populations at Increased Risks of Ultraviolet Radiation-Induced Skin Cancers

Besides fair-skinned persons, other special populations at increased risks of UV-induced skin cancers include children and organ transplant recipients (OTRs) (Centers for Disease Control and Prevention 2011). In children, skin cancer risks associated with UV exposures are greater for CMM than for NMSCs (Centers for Disease Control and Prevention 2011). Since 80% of major sun overexposures occur before the age of 18 years, children are at the greatest risk of developing CMM as young adults (Centers for Disease Control and Prevention 2011). Children who have suffered blistering sunburns are five times more likely to develop CMM as young adults than children who have never had sunburns (Centers for Disease Control and Prevention 2011).

Epidemiological investigations have now supported associations between UV exposures and NMSCs in immunosuppressed OTRs (Terhorst et al. 2009). In 2009, Terhorst and coinvestigators assessed the risk factors for NMSCs in OTRs in a questionnaire study that enrolled 70 OTRs who had developed skin cancer after transplantation compared to 69 matched OTRs who had no history of skin cancer (Terhorst et al. 2009). The investigators found the skin cancer group to have fairer skin color than controls ($p < .05$), to have received greater recreational sun exposures ($p < .05$), and to have been transplanted at younger ages ($p < .001$) for longer time periods ($p < .001$) than controls (Terhorst et al. 2009). In addition, the skin cancer group was more likely to have a past or present history of immunosuppression with azathioprine ($p < .05$) (Terhorst et al. 2009).

In addition to UV-exposed transplant recipients and patients with oncogenic viral infections, patients with two rare, genetic skin diseases, epidermodysplasia verruciformis and xeroderma pigmentosum (XP), will also demonstrate enhanced UV-induced inflammation and a higher incidence of NMSCs in sun-exposed body sites (Kraemer et al. 1978). Patients with XP have mutations that inhibit DNA repair following UV-induced DNA damage and demonstrate a significant propensity to develop NMSCs following UV exposures, up to 5000 times that of the general population (Kraemer et al. 1978).

UV exposures are well-known stimuli for reactivations of type 1 HSV infections presumably from suppression of local immune responses that permit immunologically unimpeded viral travel down sensory nerves and subsequent replication at sites of initial viral infections (Ichihashi et al. 2004). In a Japanese study of 2656 patients with recurrent HSV infections, the self-reported cause of recurrent cold sores was solar UV exposure in 10.4%, rising to 19.7% overall and 40% in subjects younger than 30 years during the summer months (Ichihashi et al. 2004). UV exposure and prior infections with cutaneous HPV can act as cofactors in the development of NMSCs presumably from a combination of complex mechanisms including UV-induced epicutaneous apoptosis, local immunosuppression, and HPV-induced malignant cell proliferation (Akgul et al. 2006).

Unlike the significant associations between UV exposures and NMSCs in transplant recipients and in patients with genetic or viral diseases, there is no evidence to support UV irradiation serving as a risk factor for hematopoietic malignancies, such as non-Hodgkin's lymphoma (Hartage et al. 1996). Although immunosuppression from cancer or antirejection chemotherapies are indeed risk factors for both NMSCs and non-Hodgkin's lymphoma, this does not support UV exposure as a common causative factor for these cancers (Hartage et al. 1996). In addition, the incidence rate of non-Hodgkin's lymphoma does not share a similar southward latitudinal gradient with the incidence rates of NMSCs in the United States (Hartage et al. 1996).

UV radiation-induced immunosuppression may be a significant risk factor for skin cancer in both immunosuppressed and immunocompetent patients and for the reactivation of viral infections with cutaneous or mucosal phases. In addition, there is some evidence for the synergistic effects of UV radiation and oncogenic HPV infections in the development of NMSCs in immunocompetent individuals. However, there is limited evidence that UV exposure can reduce the efficacy of vaccination.

In a large, Dutch case–control investigation on UV exposure and immune response to vaccination, study subjects were vaccinated with the recombinant hepatitis B vaccine following five consecutive days of whole body UV irradiation (Sleijffers et al. 2001). Only those study subjects with a particular interleukin 1B polymorphism showed significantly suppressed antibody responses to hepatitis B virus vaccine, if exposed to UV irradiation prior to vaccination (Sleijffers et al. 2001).

In a 2011 review article, Norval and Woods reviewed studies on UV-induced immunosuppression and the efficacy of vaccination, and described a limited number of animal and human models of vaccination that did demonstrate UV-induced reduction in the efficacy of vaccination (Norval and Woods 2011). The authors recommended further evaluation of the role of UV radiation-induced immunosuppressive effects on the efficacy of certain vaccinations and noted that both the primary and delayed immune responses to several antigens, including microbial antigens, could be reduced by UV radiation exposures (Norval and Woods 2011).

1.02.4.8 Adverse Health Effects of Excessive Ultraviolet Radiation in Children

Worldwide, the burden of environmental disease is significantly greater for children than adults, especially for children under 5 years of age (Pronczuk and Surdu 2008). Unlike adults, children are often exposed to multiple environmental threats simultaneously, such as high UV index and ozone alerts that are often combined with other behavioral, social, and economic risk factors (Pronczuk and Surdu 2008). Environmental risk factors including climate, ozone depletion, air pollution, deforestation, and desertification have been estimated to contribute more than 33% of the disease burden in children worldwide (Pronczuk and Surdu 2008). Environmental factors contribute 36% to all deaths and 34% to the overall disease burden in children between 0 and 14 years of age (Pronczuk and Surdu 2008). The major health risks in children that are magnified by environmental threats include (1) diarrheal diseases and malnutrition (1.6 million deaths per year), (2) acute upper respiratory infections (1 million deaths per year), and (3) malaria (1 million deaths per year) (Pronczuk and Surdu 2008).

In the United States, one-third of residents report at least one sunburn per year (Hall et al. 2003). Sunburn is the adverse health effect most commonly experienced by children every year due to excessive UV-B exposure from stratospheric ozone depletion (Hall et al. 2003). Fair-skinned people are the most susceptible to sunburn and will run a correspondingly higher risk of long-term adverse effects, especially skin cancers. In children, skin cancer risks associated with UV exposures are greater for melanomas than for NMSCs (Westerdahl et al. 1994).

Major risk factors for melanoma include solar exposures to UV-A and UV-B with three or more blistering sunburns before 20 years of age (Holman and Armstrong 1984; Centers for Disease Control and Prevention 2011; Westerdahl et al. 1994). Since 80% of major sun overexposures occur before the age of 18 years, children are at the greatest risk of developing melanomas as young adults (Centers for Disease Control and Prevention 2011). Children who have suffered blistering sunburns are five times more likely to develop melanomas as young adults than children who have never had sunburns (Centers for Disease Control and Prevention 2011). Melanoma is now the most commonly increasing malignancy worldwide and is the most common cancer among people 25–29 years of age (Holman and Armstrong 1984; Centers for Disease Control and Prevention 2011; Narayanan et al. 2010; Diepgen and Mahler 2002). Melanoma kills about 100 000 people each year, 7000 in the United States (Holman and Armstrong 1984;

Centers for Disease Control and Prevention 2011; Narayanan et al. 2010; Diepgen and Mahler 2002).

In addition to increased melanoma risks from UV radiation, children are at a greater risk for recurrent upper respiratory infections than adults from combinations of the damaging effects of ozone on airways and UV-induced immunosuppression. High ozone levels can cause exacerbations of asthma and other reactive airway diseases that are prevalent in childhood, such as bronchiolitis and tracheobronchitis or croup. Viral infections with skin phases, such as HSV (cold sores) and papilloma (warts), are also more prevalent in children than in adults and can be reactivated by UV exposures (Ichihashi et al. 2004; Akgul et al. 2006).

In 2005, Hrushesky and coinvestigators in the Netherlands reported an unanticipated seasonal fluctuation in the frequency of cervical smears positive for oncogenic, anogenital HPV types during the summer months of highest solar UV exposures, with a peak in August (Hrushesky et al. 2005, 2006). The investigators concluded that UV-induced immunosuppression could be an important contributor to the increase in active HPV infections of the cervix during the summer months in addition to unprotected sex among adolescents and young adults during summer vacations (Hrushesky et al. 2005, 2006). Although this single reported association between summertime UV exposures and cervical HPV infections has not been confirmed and is confounded by multiple behavioral risk factors, the importance of this finding for young adults is that sexually transmitted infections with the high-risk anogenital HPV types are often acquired at early ages and are estimated to cause fatal anal and cervical cancers in over 500 000 young women worldwide every year (Hrushesky et al. 2005, 2006).

The last potential adverse health impact of excessive UV irradiation in children could be on the reduced efficacy of primary and booster series vaccinations for the most common viral infectious diseases of childhood, especially measles (Sharma et al. 2004). Measles is of the greatest concern because of its ease of airborne transmission, exacerbation by malnutrition and vitamin deficiencies (especially vitamin A), frequently devastating (blindness) or fatal outcomes in unvaccinated children, and high prevalence among displaced and overcrowded populations (Sharma et al. 2004). In 2004, Sharma and colleagues investigated an outbreak of measles in a city in India and observed that one-third of the cases had occurred in children who had previously been vaccinated against measles and who should have been protected (Sharma et al. 2004). The authors concluded that the virus-specific immunity could have waned in the vaccinated children who contracted measles because of solar UV-induced immunosuppression, although immunological evidence was not presented to support their conclusion (Sharma et al. 2004).

1.02.5 Ecosystem Effects of Excessive Ultraviolet Radiation

Excessive UV radiation from stratospheric ozone depletion has had significant adverse effects on both marine and terrestrial ecosystems, with significant implications for the aquatic food chain, marine fisheries, agricultural soil quality, and agricultural crop productivity. Plants are important components of both marine (phytoplankton, cyanobacteria) and terrestrial ecosystems and depend on solar UV radiation to catalyze the photochemical production of oxygen by photosynthesis (Caldwell et al. 2007). With the exception of motile phytoplankton, most plants cannot escape from UV radiation. Unlike animals and humans, plants have reduced capacities to produce subsurface melanin-like, UV-absorbing chemicals to protect themselves from excessive UV radiation. The adverse impact of UV irradiation on marine and terrestrial ecosystems has been studied extensively in environmental sentinel organisms since the 1970s when CFCs were first recognized as substances that deplete stratospheric ozone. Sentinel animals closely studied in terrestrial ecosystems have included earthworms and amphibians (frogs, salamanders) as surrogates for soil and freshwater ecosystem health, respectively (Misra et al. 2005; Blaustein and Johnson 2003; Ballaré et al. 2011; Lamare et al. 2011). Sentinel animals closely studied in marine ecosystems have included the echinoderms (sea urchins, sand dollars) and other invertebrates and larval fish as surrogates for the health of the marine food chain and commercial marine fisheries (Misra et al. 2005; Blaustein and Johnson 2003; Ballaré et al. 2011; Lamare et al. 2011; US Environmental Protection Agency, 2011).

1.02.5.1 Effects of Ultraviolet Radiation on Terrestrial Ecosystems

The damaging effects of excessive UV-B radiation on plants occur by direct damage to leafy vegetation and indirect damage by bio-geochemical deterioration of soil oxygenation and quality. Excessive solar UV exposures can directly burn, desiccate, discolor (silver leafing), and kill leaves and limit photosynthesis and plant growth (Caldwell et al. 2007; Ballaré et al. 2011). Indirect damage from UV radiation can create soil sinks of primary (carbon monoxide) and secondary photochemical (ozone) air pollutants, reducing soil oxygenation, altering nutrient distribution, limiting plant growth, and disrupting biological synchronization during critical developmental stages (Caldwell et al. 2007; Ballaré et al. 2011). The cascading effects of these excessive UV-induced adverse effects on agriculturally important plants include reduced resistance to plant pathogens, alternating growth spurts and stunts, and an inability to maintain competitive balance against insect pests and noxious weeds (Caldwell et al. 2007; Ballaré et al. 2011).

As noted, earthworms and amphibians have now been identified as sensitive monitors of the adverse effects of excessive UV radiation on terrestrial ecosystems for several reasons (Misra et al. 2005). Earthworms are the sentinels of soil pollution because they represent 80% of the total biomass of all soil invertebrates and their skin is permeable and contains several UV-sensitive sterols similar to the cholesterols in human skin that are precursors for active vitamin D (Misra et al. 2005). Frogs are the sentinels of air and freshwater pollution because they also have permeable skins, lay eggs without shells, and live in freshwater ecosystems with their large eyes constantly seeking prey and absorbing UV radiation (Blaustein and Johnson 2003).

Misra and coinvestigators studied dose-related effects of solar UV radiation on the earthworm, *Metaphire posthuma*, by measuring the generation of reactive oxygen species (singlet oxygen molecules, superoxide anions, and hydroxyl radicals), the photooxidation of lipids, and histopathological changes in earthworm integument (Misra et al. 2005). The authors reported significant dose–response effects from increasing doses of solar irradiation on the generation of reactive oxygen species and lipid peroxidation by-products (Misra et al. 2005). In addition, significant histopathological anomalies including thickening, vacuolization, and hypertrophy of epicutaneous cells occurred when earthworms were exposed to solar irradiation for 1–2 h, while 3-h exposure periods caused subepicutaneous muscular degeneration (Misra et al. 2005). Continuous exposure to solar irradiation for more than 3 h was lethal for earthworms (Misra et al. 2005). The investigators concluded that the 2004 levels of UV radiation in sunlight could produce significant phototoxic effects in earthworms by photodynamic action and generation of reactive oxygen species (Misra et al. 2005). Increases in the amount of UV radiation in sunlight from stratospheric ozone depletion was even more damaging to the ultrastructural elements in earthworm skin and resulted in fatalities in a dose–response manner (Misra et al. 2005).

1.02.5.2 Case Studies in Ozone Depletion III: Explaining Frog Deformities

Frogs are sensitive, sentinel monitors of water quality because of their aquatic habitats, permeable skins, and unshelled eggs laid on water surfaces. As early as 1989, scientists had recognized that congenital limb deformities impaired amphibian survival and contributed to dramatic declines in freshwater frog populations (Blaustein and Johnson 2003). Scientists were concerned that the potential environmental risk factors affecting frog survival would soon begin to impact other animal species.

Between 1994 and 1998, Blaustein and Johnson demonstrated that exposure to UV radiation could kill amphibian embryos and larvae, cause serious eye damage in frogs, and induce various types of congenital anomalies in the bodies of both frogs and salamanders (Blaustein and Johnson 2003). Between 1996 and 1998, Johnson and coinvestigators continued their amphibian deformity studies in broad surveys of California wetlands and discovered that the ponds filled with frogs with abnormal limbs were also infested with aquatic snails infected with a flatworm, *Ribeiroia ondatrae* (Blaustein and Johnson 2003). The infective cysts of the flatworms were found densely clustered below the skin at the base of deformed hind legs in the tree frogs living in the parasite-infested ponds (Blaustein and Johnson 2003). The investigators then experimentally infected other tree frogs with the same parasites, which developed similar hind limb deformities (Blaustein and Johnson 2003). The scientists concluded that immune system suppression from UV irradiation was responsible for opportunistic parasitic infections in frogs and significantly associated with extra, missing, or deformed hind legs (Blaustein and Johnson 2003). Other observed deformities included congenital blindness and skin defects that were not associated with parasitic infections and were also attributed to UV radiation overexposures (Blaustein and Johnson 2003). The significant human health impact of diseased and declining frog and other amphibian populations in freshwater wetlands as a result of increased UV radiation will be a significant loss of effective biological controls of arthropod vectors of infectious diseases, especially mosquitoes—highly competent vectors of viral (dengue, Chikungunya, yellow fever, Japanese encephalitis, and other encephalitides), protozoal (malaria), and parasitic (filariasis) diseases.

In summarizing the effects of solar UV radiation on terrestrial ecosystems, Ballaré and coinvestigators highlighted the following four key points (Ballaré et al. 2011). (1) The effects of UV-B on the growth of terrestrial plants are relatively small and, because the Montreal Protocol has been successful in limiting ozone depletion, the reduction in plant growth caused by increased UV-B radiation in areas affected by ozone decline since 1980 is unlikely to have exceeded 6%. (2) Solar UV-B has large direct and indirect (plant-mediated) effects on canopy arthropods and microorganisms. Therefore, trophic interactions (herbivory, decomposition) in terrestrial ecosystems appear to be sensitive to variations in UV-B irradiance. (3) Future variations in UV radiation resulting from changes in weather patterns and land use may have more important consequences on terrestrial ecosystems than the changes in UV caused by ozone depletion. This is because the resulting changes in UV radiation may affect a greater range of ecosystems, and will not be restricted solely to the UV-B component. (4) Several ecosystem processes that are not particularly sensitive to UV-B radiation can be strongly affected by UV-A (315–400 nm). One example is the physical degradation of plant litter. Increased photodegradation (in response to reduced cloudiness or canopy cover) will lead to increased carbon release to the atmosphere via direct and indirect mechanisms. (Ballaré et al. 2011).

1.02.5.3 Effects of Ultraviolet Radiation on Aquatic Ecosystems

Although UV radiation is gradually attenuated by the depths of the marine water column, UV-A and UV-B radiation can penetrate to depths of greater than 16 m (10% of surface UV-B) and 46 m (10% of surface UV-A) and exert significant impact on marine organisms (US Environmental Protection Agency 2011; Lamare et al. 2004). The effects of UV radiation have been studied on several marine species including phytoplankton, cyanobacteria, echinoderms and other invertebrates, and fish (Smith et al. 1992, Lamare et al. 2011, 2004; US Environmental Protection Agency 2011; Singh et al. 2010; Dahms and Lee 2010; Perotti and del Carmen Disguez 2006).

Phytoplankton are the foundation of the marine food chain and are restricted to the upper marine water column, the euphotic zone, where there is enough solar radiation to support photosynthesis and plankton productivity. Although most of the movements of phytoplankton are influenced by the physical actions of currents, tides, and waves, phytoplankton are also capable of active movement and positioning sensing to enhance their productivity and survival. Scientific investigations have demonstrated that UV-B irradiation can affect both the motility and the orientation mechanisms of phytoplankton in the euphotic zone, resulting in reduced productivity and survival rates (US Environmental Protection Agency 2011; Singh et al. 2010).

Solar UV-B radiation at current levels has also been found to damage the reproductive capacity and early developmental stages of echinoderms, crustaceans, and fish (Dahms and Lee 2010; Lamare et al. 2004; Perotti and del Carmen Disguez 2006). Small increases in UV-B exposures in marine ecosystems will further reduce productivity and survival of both phytoplankton and smaller marine creatures, reducing the size of the marine population that depends on these organisms for survival, with significant impact on commercial fisheries. The ultimate impact on humans would be a reduction in the availability of seafood proteins and cardioprotective omega-3 polyunsaturated fatty acids.

Like the phytoplankton, cyanobacteria that inhabit the euphotic zone of the marine water column are also capable of photosynthesis and participate in the marine food chain (Singh et al. 2010). UV radiation has both direct effects on cyanobacteria because of absorption by biomolecules and indirect effects by inducing oxidative stress with DNA damage (Singh et al. 2010). Cyanobacteria have, however, developed several effective strategies for defense against UV radiation, including not only avoidance behaviors similar to phytoplankton but also synthesis of UV-absorbing compounds such as the mycosporine-like amino acids and scytonemin (Singh et al. 2010). In addition, cyanobacteria can respond rapidly to UV-induced oxidative stresses by DNA screening and repair mechanisms or by programmed cell death (apoptosis) (Singh et al. 2010). In summary, the cyanobacteria are primitive prokaryotes that first appeared on Earth before there was a stratospheric ozone layer and may be key organisms to study in the development of new UV-absorbing compounds for broad-spectrum sunscreens because of their unique UV defenses (Singh et al. 2010).

The echinoderms are also ubiquitous in the marine environment, are long-lived, dominate the benthic macrofauna, and contribute to the marine food chain (Lamare et al. 2011). UV radiation negatively impacts echinoderms by causing DNA damage and mutations (Lamare et al. 2011). However, similar to the cyanobacteria, echinoderms have evolved defense strategies against UV radiation including UV-absorbing pigments (carotinoids, melanin, and mycosporine-like amino acids), antioxidants to counter oxidative stress, and DNA screening and repair mechanisms (Lamare et al. 2004, 2011; Singh et al. 2010). The echinoderms are motile like phytoplankton and also utilize avoidance behaviors to limit their UV radiation exposures (Lamare et al. 2004, 2011).

UV radiation can also cause cellular and molecular damage in fish despite defense mechanisms that include better avoidance behaviors and UV-absorbing pigments than echinoderms and phytoplankton (Perotti and del Carmen Disguez 2006). UV radiation impairs sperm motility, reduces fertility, interferes with embryo cleavage, and causes embryo and neonatal malformations that can threaten the sustainability of natural finfish populations (Perotti and del Carmen Disguez 2006). Perotti and Dieguez studied the health effects of enhanced levels of UV radiation in three species of Patagonian anurans in southern Argentina, an area near and often within the Antarctic ozone hole (Perotti and del Carmen Disguez 2006). Anuran fish were selected for the study because they are ubiquitous in shallow waters and breed during the austral spring when UV-B levels are the highest in the southern hemisphere (Perotti and del Carmen Disguez 2006). The researchers reported a UV dose–response increase in congenital malformations, but not in survivorship (Perotti and del Carmen Disguez 2006). The fish that received the highest levels of UV radiation also presented higher concentrations of UV-absorbing melanin, suggesting that solar UV exposure triggered photoprotection by pigments (Perotti and del Carmen Disguez 2006). Most marine species have developed behavioral, cellular, and molecular mechanisms to protect themselves from enhanced UV radiation, all of which deserve further study.

Although several studies have now demonstrated the negative impacts of UV-B radiation on both the primary aquatic food web producers (cyanobacteria, phytoplankton, macroalgae, and aquatic plants) and their consumers (zooplankton, crustaceans, amphibians, fish, and corals), Häder and coinvestigators have raised the following two important questions regarding the ultimate impact of solar UV-B radiation on carbon dioxide absorption and on species composition within aquatic ecosystems and on the interaction of organisms between the trophic levels within aquatic ecosystems (Häder et al. 2011). (1) Will a UV-B radiation-induced decrease in the population size of the more sensitive primary producers be compensated for by an increase in the population size of the more tolerant species yielding a net negative impact on the absorption of carbon dioxide by aquatic ecosystems? (2) Will there be a significant impact on the quantity and quality of nutrients cycling through the aquatic food web, including the generation of aquatic food proteins for humans?

1.02.6 Human Adaptive Strategies for Ozone Depletion and Excessive Ultraviolet Radiation

The most important adaptive strategies for people to adopt to protect themselves from excessive UV radiation from stratospheric ozone depletion are to protect their skin and eyes from sun damage by using and selecting proper sunscreens and wearing tinted eyeglasses (Table 5). The skin and eyes must be protected from both the sunburn effects of UV-B and the deeply penetrating effects of UV-A.

Today, most sunscreens are composed of combinations of organic chemicals to absorb UV light (padimate, oxybenzone), inorganic chemicals to filter and reflect UV light (titanium dioxide, zinc oxide), and newer organic particles to both absorb and reflect UV light (Parsol®, Tinosorb®, Uvinul®). Historically, sunscreens were developed for protection from sunburn from UV-B only. As a result of new federal regulations in the United States, sunscreens labeled as "broad spectrum" are protective for both UV-B and UV-A irradiation for a period of time (the sun protection factor (SPF)) before damaging sunburns. A sunscreen with an SPF of 15 properly applied (defined as $2\ \mathrm{mg\,cm^{-2}}$ (Molina and Rowland 1974) of sun-exposed skin) will protect one from 93% of UV-A and UV-B radiation; SPF 30 is protective against 97% of UV-A and B; SPF 50 is protective against 98% of UV-A and B. Table 7 lists some of the most common sunscreen ingredients stratified as either absorbents or physical filters/receptors used in broad-spectrum sunscreens that are protective in combined proprietary sunscreens against both UV-A and B.

1.02.6.1 Public Perceptions Regarding Safe Solar Ultraviolet Radiation Exposures

Ezzedine and coinvestigators have studied sun exposure behaviors in large subcohorts of survey-responding travelers, nontravelers, and expatriates nested in a larger cohort of 12 741

Table 7 The most common US Food and Drug Administration (FDA)-approved sunscreen ingredients used in broad-spectrum sunscreens

Sunscreen ingredients	*UV-A-1 range (340–400 nm) covered*	*UV-A-2 range (320–400 nm) covered*	*UV-B range (290–320 nm) covered*
UV absorbers in sunscreens			
Aminobenzoic acid (para-aminobenzoic acid (PABA))	−	−	+
Avobenzone	+	−	−
Cinoxate	−	−	+
Dioxybenzone	−	+	+
Ecamsule (mexoryl SX)	−	+	−
Ensulizole (phenylbenzimiazole sulfonic acid)	−	−	+
Homosalate	−	−	+
Menthyl anthranilate	−	+	−
Meradimate	−	+	+
Octocrylene	−	−	+
Octinoxate (octal methoxycinnamate)	−	−	+
Octal salicylate (octisalate)	−	−	+
Octocrylene	−	−	+
Oxybenzone	−	+	+
Padimate O	−	−	+
Sulisobenzone	−	+	+
Trolamine salicylate	−	−	+
Inorganic physical filters and reflectors			
Titanium dioxide	+	+	+
Zinc oxide	+	+	+

+, UV range canceled; −, UV range not canceled.

French adult volunteers enrolled in the SU.VI.MAX cohort and observed the following results (Ezzedine et al. 2007a,b; Autier 2009). (1) Women travelers reported more frequent sun exposures over the past year, sun bathed in high UV-index areas daily for more than 2 h, and experienced more intensive sun exposures than nontravelers (Ezzedine et al. 2007a) (2) Although the use of sun protection products was similar in all travelers and nontravelers, women used sunscreens with higher SPFs more often and more regularly than men (Ezzedine et al. 2007a).

In a similarly designed study, the same investigators sent sun exposure and sun protection behavior questionnaires twice to all subjects in the SU.VI.MAX cohort, with 1694 respondents reporting travel to a tropical or high UV-index country during their lifetimes for more than three consecutive months (expatriates) (Ezzedine et al. 2007b) The investigators described the following results (Ezzedine et al. 2007b). (1) Female expatriates reported more frequent deliberate sun exposures, more sunbathing between 11 a.m. and 4 p.m., less gradual sun exposure, more intensive sun exposures, more exposures during nautical sports, and more nude exposures than female nonexpatriates (Ezzedine et al. 2007b). (2) Male expatriates reported more frequent intensive sun exposures and more skin exposures during nautical and mountain sports than male nonexpatriates (Ezzedine et al. 2007b) In summary, Ezzedine and coinvestigators have now registered a large cohort of French adults to study for sun exposure and protection behaviors in tropical and high UV-index countries for short and prolonged stays, and their results have repeatedly demonstrated that travelers would benefit from more pretravel advice regarding sun exposures and sun protective behaviors (Ezzedine et al. 2007a,b; Autier 2009).

Other studies have now closely investigated public attitudes, knowledge levels, and behavioral practices regarding sunscreen use. In 2006, Autier reported sunscreen abuse by persons intentionally seeking to expose themselves to sunlight for excessively prolonged periods (Wright et al. 2001). Wright and coinvestigators evaluated the attitudes toward sunscreen effectiveness and found that 47% of study subjects reported staying out longer in the sun after applying sunscreen (Ezzedine et al. 2008). In 2008, Ezzedine and coinvestigators reported the results of a cross-sectional study on artificial and natural tanning behaviors in a French national cohort of 7200 adults (Autier 2009). The investigators determined that indoor tanners were also regular sunbathers unconcerned about the risks of combined indoor and outdoor UV exposures (Autier 2009). In a 2009 survey assessment of sunscreen knowledge, Wang observed that only 48.2% of survey respondents knew that “SPF” was the acronym for “sun protection factor” (Wang and Dusza 2009).

Regarding the proper application of sunscreens, quantity and frequency of use remain among the most important factors limiting sunscreen efficacy (Wang and Dusza 2009; Kullavanijaya and Lim 2005; Lim and Cooper 1999; Sunscreens: An Update 2008). The international standard quantity of sunscreen application used to determine SPF factors is 2 mg cm^{-2}. (Sunscreens: An Update 2008; Diffey 2001). However, Diffey observed that most people apply only 0.5–1.5 mg cm^{-2} of sunscreen and do not reapply sunscreens after swimming or excessive sweating (Diffey 2001). In summary, observational studies have now demonstrated that the public often abuses sunscreens for intentional UV overexposures and knows little about proper sunscreen protection, selection, and use (Ezzedine et al.

2007a,b, 2008; Autier 2009; Wright et al. 2001; Sunscreens: An Update 2008; Diffey 2001).

1.02.6.2 What Are the Most Effective Prevention Strategies for Protection from the Adverse Health Impact of Solar Ultraviolet Radiation?

The primary prevention strategies for protection from the adverse health impact of solar radiation include the following. (1) Limit exposure to UV radiation, especially between 10 a.m. and 4 p.m. (2) Wear sun protective clothing and UV-A- and UV-B-protective sunglasses. (3) Use sunscreens with an SPF of 15 or higher depending on your skin type. (4) Avoid all artificial tanning devices. (5) For children younger than 6 months of age, always use hats, clothing, and shading, rather than sunscreens. (6) Encourage all children to practice the shadow rule: seek shade whenever your shadow is shorter than you are tall.

The secondary prevention strategies for protection from the adverse health impact of solar radiation focus on screening and early detection of skin cancers and include the following. (1) Be aware of new skin lesions and practice frequent skin examinations. (2) Know the warning signs of melanoma or the ABCD rule (asymmetry, border irregularity, variable color, and diameter greater than 6 mm). (3) Seek immediate physician consultation for evaluation of any new or persistent skin marks or any changes in preexisting skin marks.

1.02.6.3 Eliminate SPF Confusion: Do You Know Your Skin Type and How to Select the Right Sunscreen?

The SPF is derived from a complex equation that calculates the amount of time it takes for UV radiation of various wavelengths to cause sunburn. In the simplest terms, the SPF is the amount of UV-B radiation required to cause sunburn on skin with sunscreen on as a multiple of the amount of time required to cause sunburn without sunscreen. In reality, several factors significantly affect the protective capabilities of the SPF number including amount of sunscreen applied, altitude, season of the year, time of the day, sweating, water exposure, reflection by snow or water surfaces, and, most importantly, skin type. Unfortunately, a very common misperception about the SPF is that if you get sunburned in 1 h, a sunscreen of SPF 15 will offer 15 h of protection. The six skin types, their definitions, and the recommended SPF for sunscreens appropriately applied by skin type are listed in Table 8. Sunscreens should always be broad-spectrum products that block both UV-A and UV-B rays, hypoallergenic, and noncomedogenic, so as not to cause rashes or clog pores, causing acne.

1.02.6.4 Do Sunscreens Really Prevent Skin Cancers?

Randomized controlled trials have now demonstrated that regular sunscreen use can prevent the development of AK (Thompson et al. 1993). Since AK are precursors of SCCs, sunscreens can prevent the development of SCCs (Thompson et al. 1993). The regular use of sunscreens may also prevent melanomas (Green et al. 2011).

1.02.6.5 Case Studies in Ozone Depletion IV: Preventing Melanomas with Regular Sunscreen Use

In 2011, Green and coinvestigators in the subtropical region of Nambour, Queensland, Australia, provided conclusive evidence from a randomized controlled trial that the regular use of sunscreens prevented melanoma (Green et al. 2011). Their study included 1621 adults randomized to regular (daily) sunscreen use ($n = 812$ persons) or to discretionary use ($n = 809$ persons), which included no sunscreen use at all (Green et al. 2011). The daily- and discretionary-use groups were well matched for skin types, nevus density, sunburn and skin cancer history, and outdoor and sun protective behaviors (Green et al. 2011). The daily users applied sunscreen with an SPF of 16 every morning to the head, neck, arms, and hands and reapplied sunscreen after sweating, bathing, or long sun exposures (Green et al. 2011). The authors found that the daily application of a broad-spectrum sunscreen with an SPF of 16 during a 5-year treatment period reduced the incidence of new primary melanomas during a subsequent 10-year follow-up period (Green et al. 2011). Ten years after trial cessation, 11 new primary melanomas were identified among the daily sunscreen group compared with 22 melanomas among the discretionary group ($p = .051$) (Green et al. 2011). The reduction in invasive melanoma incidence was even more substantial with 3 invasive melanomas in the daily-use group compared to 11 in the discretionary group ($p = .045$) (Green et al. 2011).

Although the Green et al. study supported the hypothesis that daily sunscreen use prevented CMM, the study prompted an immediate series of subsequent editorials that challenged the significance and the external validity of the reported findings. The major limitations of the study were identified as (1) low statistical power to detect significant differences if present, (2) variable interpretations of CMM invasiveness by many pathologists, (3) selection of less rigid test statistics, (4) unblinded investigators, (5) exclusions of CMMs on the trunk and the extremities, (6) limited applications to populations other than the light-skinned Australians of Nambour, and (7) the borderline significance of p-values near .05 (Gimotty and Glanz 2011; Golderhersh and Kowlowsky 2011; Doré 2011).

Table 8 Know your skin type and select the right sunscreen

Skin type	*Skin color (other common descriptors)*	*Sun exposure effects*	*Recommended sunscreen SPF*
I	White (Celtic or albino, freckles common)	Always burns, never tans	30+
II	Light (European)	Always burns, rarely tans	30+
III	Light-intermediate or beige (dark European)	Sometimes burns, sometimes tans	15+
IV	Olive or beige with brown tint (Mediterranean)	Tans easily, burns less	15+
V	Brown	Tans easily, rarely burns	15+
VI	Black	Does not burn	15+

Courtesy Fitzpatrick scale.

1.02.7 Mitigation Strategies for Stratospheric Ozone Depletion

The most successful climate mitigation strategy, aimed at preserving the ozone layer, is the Montreal Protocol on Substances that Deplete the Ozone Layer, the Vienna Convention for the Protection of the Ozone Layer, and public–private partnerships, such as the Green Chill Advanced Refrigeration Partnership and the Responsible Appliance Disposal (RAD) Program in the United States. All 196 UN nations in the world have now ratified the Montreal Protocol and the Vienna Convention, making these two international treaties the first and only treaties in the world to achieve universal ratification. At the Nineteenth Meeting of the Parties to the Montreal Protocol in September 2007, all party nations agreed to more aggressively phase out the ozone-depleting hydrochlorofluorocarbons (HCFCs), early substitutes for the CFCs in widespread use today as refrigerants, solvents, and insulators. The agreement to adjust the phase-out schedule for HCFCs is expected to reduce atmospheric emissions by 47%, compared to earlier commitments, and for the developing nations, the agreement would result in a 58% reduction over 30 years. The climate effects of stronger HCFC phase-out commitments would depend on technological choices to replace the HCFCs and have been estimated to represent a phase-out of more than 9000 metric tons of carbon dioxide equivalent emissions over 30 years, or the equivalent of removing the automotive emissions of 55 million US passenger cars (40% of the US national passenger car fleet) each year for the next 30 years. The most significant outcomes of the international treaties to protect the ozone layer and the world's climate have been to send clear signals to world markets about the needs to develop new alternatives for ozone-depleting substances that do not harm the ozone layer or other aspects of the climate system.

Public–private partnerships also offer successful mitigation strategies for limiting ozone depletion and resulting alterations in climate patterns. The Green Chill Advanced Refrigeration Partnership is a US EPA cooperative alliance with the supermarket industry and other stakeholders to promote advanced technologies, strategies, and practices that reduce the amount of refrigerants used in equipment and released into the atmosphere. In 2007, Green Chill partners reduced emissions of ozone-depleting refrigerants by 30 metric tons and greenhouse gas emissions by 2.5 million metric tons of carbon dioxide equivalents, or the equivalent of avoiding the emissions of 0.5 million passenger cars in 1 year.

The RAD Program is another US EPA voluntary public–private partnership with retailers, utilities, universities, municipalities, and manufacturers to responsibly dispose of appliances that use ozone-depleting substances as refrigerants and insulators, primarily freezers and refrigerators. The partners in the RAD Program have achieved substantial benefits for the ozone layer and for climate by using best practices to ensure that all refrigerants and insulating materials are recovered or destroyed properly. In 2008, RAD partners disposed of more than 1 million refrigerant-containing appliances and reduced greenhouse gas emissions by over 4 million metric tons of carbon dioxide equivalents, or the equivalent of avoiding the emissions of 0.92 million passenger cars in 1 year.

1.02.7.1 The Public Health and National Financial Burdens of Skin Cancers: Recommendations for Policymakers

Skin cancer is the most common cancer in the United States and in several other nations, such as the United Kingdom, Australia, and New Zealand (Guy and Ekwueme 2011). Skin cancer is costly to treat in advanced stages, places significant financial burdens on national health care delivery systems, and results in significant losses in productivity and quality of life. Recently, Guy and Ekwueme conducted a meta-analysis of the world's peer-reviewed literature on the years of productive life lost (YPLL) and the indirect costs of melanoma and NMSCs in the United States (Guy and Ekwueme 2011). The investigators identified 16 relevant studies meeting their inclusion criteria, 6 from the United States and 10 from other industrialized nations (Guy and Ekwueme 2011). The mean number of YPLL per death from skin cancer was 15 years for melanoma and 10 years for NMSCs (Guy and Ekwueme 2011). The indirect costs attributable to melanoma and NMSCs ranged from $US28.9–39.2 million for morbidity to $US1.0–3.3 billion for mortality, respectively (Guy and Ekwueme 2011). The authors concluded that skin cancers led to significant increases in YPLL and indirect costs associated with premature morbidity and mortality and recommended greater governmental support of prevention and detection programs to reduce the prevalence of skin cancers, to improve national productivity, and to reduce the cost burdens on health care systems (Guy and Ekwueme 2011).

Skin cancer diagnoses and treatments represent the single-most costly burden to the national health care systems of Australia and New Zealand (Guy and Ekwueme 2011; Brougham et al. 2010). As a result of the excessive economic burden of skin cancer on health care delivery systems, nations have developed several innovative programs to improve early detection and treatment of skin cancers including targeted screening of high-risk populations and phototriage for early referrals for skin cancer diagnoses and treatments (Swetter et al. 2003; Morton et al. 2011; McCarthy 2004).

In 2004, Swetter and coinvestigators with the US Veterans Administration designed a targeted skin cancer screening program for high-risk US veterans with minimal to no prior dermatologic care (Swetter et al. 2003). The investigators reported that of 374 patients (362 men, 12 women, mean age 63.4 years) screened for skin cancers in California over a 3-year period, 54% ($n = 203$) had a positive screen, including 139 with presumptive actinic keratosis, 41 with BCC, 9 with SCC, and 14 with dysplastic nevus versus melanoma (Swetter et al. 2003). The investigators concluded that targeting a high-risk population of predominantly elderly, Caucasian men yielded high detection rates of premalignant and malignant skin lesions and resulted in more efficient referrals for definitive treatment of premalignant conditions and skin cancers in early stages (Swetter et al. 2003).

Recently, Morton and coinvestigators in the United Kingdom conducted an observational study to compare the utility and cost-effectiveness of conventional versus phototriage referral pathways for presumptive skin cancers (Morton et al. 2011). Phototriage meant that patients would initially be sent to medical photographers in community health centers for high-quality photographs and dermatoscopic images of skin lesions to be later reviewed by dermatologists for referrals (Morton et al. 2011). Phototriage permitted 91% of patients (263/289) to achieve definitive care at their first visit to either a community or specialty treatment center compared with only 63% (117/186) via the conventional referral pathway (Morton et al. 2011). The mean waiting time to definitive treatment was reduced on the phototriage pathway; there was a 72% reduction in referrals to specialty clinics, freeing up capacity; and, despite the costs of photography, there was a cost saving of £UK1.70 per patient using phototriage (Morton et al. 2011).

Policymakers are encouraged to support both primary and secondary prevention programs for skin cancer because skin cancers place significant burdens on national productivity and health care delivery and costs. Primary and secondary prevention programs should be targeted at decision makers and high-risk groups. For example, primary prevention programs, such as Australia's "Slip, Slop, Slap, Seek, and Slide" program, targeted at the parents of young children and adolescents have resulted in greater public awareness of the risks of UV irradiation and skin cancer and a reduction in deaths from melanomas in regular sunscreen users (McCarthy 2004). Screening programs targeted at elderly, fair and light-skinned persons who have minimal to no prior dermatologic care are successful in detecting skin cancers at earlier stages when the costs of definitive treatment are less (Swetter et al. 2003). Lastly, innovative technologies, such as telemedicine and phototriage, can also improve screening for skin cancer, result in earlier referrals for definitive treatment, and reduce health care costs while freeing up capacity in specialty clinics (Morton et al. 2011).

1.02.7.2 Case Studies in Ozone Depletion V: "Slip, Slop, Slap, Seek, and Slide"

Australia receives 15% more solar UV radiation than equivalent locations in the northern hemisphere and has the highest incidence rates for skin cancers in the world, with 2002 age-standardized incidence rates for BCC of 1150/100 000, for SCC of 560/100 000, and for melanoma of 40/100 000 (McCarthy 2004). As a result, Australia has developed highly successful primary prevention programs for skin cancer awareness initially focused on sunscreen use with a reduction in melanoma deaths and currently refocused on sun avoidance and targeted at the highest risk groups for lifetime UV exposures, children, and adolescents. As in other nations, primary prevention programs in Australia are often based on state and nongovernmental organization partnerships.

In the 1980s, the Victoria Anti-Cancer Council, an affiliate of the Australian Cancer Council, launched the "Slip, Slop, Slap" program, meaning "*Slip* on a shirt, *Slop* on sunscreen, *Slap* on a hat, *Seek* shade, and *Slide* on sunglasses" (McCarthy 2004). The program was targeted at school-age children and adolescents, presented in multiple media formats from cartoons to radio and televised public messages, and was often promoted at beachfronts and sporting events. Since then, all other states in Australia have adopted similar skin cancer prevention programs with the clear message of "sense in the sun" as being compatible with the Australian environment and an outdoor lifestyle (McCarthy 2004). Although adolescents remain more resistant than younger children to "sense in the sun" campaigns in Australia and elsewhere, the success of "Slip, Slop, Slap, Seek, and Slide" programs has resulted in "no hat, no play" policies at schools and behavior modification by the parents of children under 10 years of age, now more likely to be seen on Australian beaches wearing hats and *Rash* shirts (tight mesh fabric shirts that remain on the wearer while in the water) (McCarthy 2004).

1.02.8 Conclusions

This chapter has addressed the factors influencing ozone levels in the atmosphere, the beneficial as well as the detrimental effects of UV radiation in man, and the environmental impact of increased UV radiation. In addition, this chapter has relied on actual case studies in stratospheric ozone depletion and excessive UV exposures in high-risk human and animal populations to describe the impact of UV radiation on human and animal health and immune status, and on aquatic and terrestrial food chains and ecosystems.

Sunbathing and other outdoor pursuits will continue to remain popular activities among residents of and travelers to temperate and tropical destinations worldwide despite the associations between excessive UV exposures and skin cancer. Health care providers should counsel families about photoprotection while outdoors and encourage everyone to take advantage of recent advances in the development of more effective broad-spectrum sunscreens and even photoprotective clothing for themselves and their children.

Although the historical ozone-depleting substances have been identified and controlled, CFC substitutes and their future replacements, such as the bromofluorocarbons and the fluoroolefins, cannot restore lost stratospheric ozone; some will further deplete stratospheric ozone for some time, and all will augment greenhouse gas effects and their secondary photochemical pollution effects in the troposphere (Tang et al. 2011). The time line to ozone layer repletion cannot be accurately predicted and will likely approach restoration slowly and asymptotically, despite new mitigation strategies and policy changes. Nevertheless, several innovative and successful strategies to reduce the adverse human health and ecosystem effects of ozone depletion have now been proposed, tested in prospective investigations, implemented nationally, and should be adopted and supported by world policymakers.

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1.03 Sea-Level Rise and Health

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Glossary

asset any item of value that potentially is exposed to hazards; can include buildings, other infrastructure, human beings, public health, ecosystems, etc.

coastal zone the potentially wide area between the dry land above the littoral and the shelf margin.

hazard a potentially harmful event.

local sea level the vertical distance between the sea surface and land surface.

global sea level the global average of local sea level

resilience the ability of a system to absorb disturbance while retaining its basic function and structure

risk the probability that a hazardous event will cause a certain damage to an asset.

vulnerability characteristic of an asset to experience damage if exposed to a hazard.

1.03.1 Introduction

Considerable work has been published on the impact of climate variability and climate change on human health (e.g., Patz et al. 2005; McMichael et al. 2006; Karl et al. 2009). However, besides a few exceptions (e.g., Nicholls et al. 2007a; Craig 2010), the question of how local sea-level rise (LSLR) may impact human health surprisingly has not received the same level of attention. Mostly, focus has been on the direct impacts of sea level-related disasters, whereas the impact of a slow rise in sea level on human health has received little attention. While there are many challenges to predicting or projecting future LSLR, even a seemingly small increase in sea level can have a dramatic impact on many coastal environments (e.g., Titus 1990). There are a number of 'domino effects' potentially triggered by LSLR that can impact human health in various ways. Storm surges amplified by LSLR would lead to more severe impacts on health infrastructure. Hurricane Katrina in 2005 demonstrated the damage of flooding to health infrastructure at a time when more health infrastructure was needed. In London, 16 hospitals are in the Thames estuary at high flooding risk (Reeder 2010), and a storm surge exceeding the capacity of the Thames Barrier would put this infrastructure at risk. In many coastal areas, potentially polluting infrastructure is exposed to inundation. For examples, in the Galveston area in the United States, an LSLR of 0.69 m could inundate or impact a total of 23 waste treatment or holding facilities (Yoskowitz et al. 2009). Ten of these sites are wastewater treatment plants; five of them contain industrial and hazardous waste; and three sites (so-called superfund sites) are highly contaminated. An inundation of these sites would lead to a high risk for the population, through reduced water and air quality, soil contamination, and pollution of coastal waters.

The impacts of LSLR and coastal protection on ecosystems (Plag and Jules-Plag 2012) also potentially could impact water and air qualities. In many regions, where coastal ecosystems are important resources for the local economy, LSLR might reduce access to these resources and thus impact the socioeconomic fabric of the local settlements.

Coastal erosion is a serious issue in many coastal areas, which has the potential to increase the local socioeconomic impacts. For example, most of the West African coasts are experiencing significant coastal erosion, and climate change and LSLR are expected to increase this trend (ACCC 2006). Coastal erosion in Lagos, the largest city in Nigeria, which on average is less than 2 m above current sea level, could rapidly move the coastline into the city. A similar situation exists for Shanghai, the largest city in China.

The possibility of a rapid LSLR in many coastal regions is increasingly recognized. It also needs to be emphasized that a rapid global sea-level rise (GSLR) is a new challenge for our civilization: never before in modern human history, with major built environments in the coastal zone, have humans been faced with a significant GSLR (Rowley et al. 2007; Orbach 2010). During the last deglaciation, rapid changes in local sea level (LSL) altered coastlines within decades. However, during that time, large-scale built environment was absent, and with much lower populations, human beings could easily adopt to shifting coastlines. Today, there is substantial built environment and crucial infrastructure in coastal zones, and urbanization of the coastal zone continues to increase. Over 600 million people live in coastal areas that are less than 10 m

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above LSL, and a large fraction of these areas can be impacted even by a small LSLR through increased inundation during storm surges. Two-thirds of the world's cities with populations over five million are located in these areas. Under these conditions, rapid changes in coastlines and increased inundation risks during storm surges would be devastating both economically and environmentally.

Adaptation and mitigation is insurance against the risk of impacts of a hazard on lives and property, including impacts on human health. For informed decision, a detailed analysis of the risk needs to take place. Crucial ingredients for risk assessments are hazard analysis, an accepted basis for determining the value of the assets potentially exposed to the hazards, and a quantitative understanding of the vulnerability of the assets to the hazards. In the following, the terminology used here for the risk-based approach to potential health impacts of LSLR is first summarized (see Section 1.03.2). A more detailed description of the methodology is given in Plag and Jules-Plag (2012). Sea level-related hazards that might impact human health directly or indirectly, including their probability density functions (PDFs), are considered next (see Section 1.03.3), followed by the assets that may be exposed to these hazards and their vulnerability (see Section 1.03.4). Finally, the authors discuss adaptation and mitigation measures to reduce the risk (see Section 1.03.5) and give recommendations to decision makers (see Section 1.03.6).

1.03.2 Risk-Based Approach to the Impact of Sea-Level Rise on Human Health

In assessing the impact of coastal LSLR on human health, the authors take a risk-based approach (Plag and Jules-Plag 2012). The concept of vulnerability to natural hazards, including climate variability, climate change, and climate change impacts, is a relatively new one, and a common language still needs to be developed (e.g., Dolan and Walker 2003). Different disciplines use different approaches with different terminologies. Therefore, the authors briefly introduce their approach, which is derived from an insurance approach. Risk is defined as the product of hazard probability times vulnerability of exposed assets times the value of the assets. The mathematical details are given in Plag and Jules-Plag (2012).

The probability of the hazard states the likelihood of a hazard of intensity I occurring during a time interval T. This probability may be time dependent. For example, at a given location x the probability of a storm surge exceeding a certain height (e.g., 3 m) within, e.g., 500 years, may change because of climate change impacting the frequency and intensity of storm surges or because of changes in the mean sea level. Thus, a risk-based approach will have to use realistic estimates of future probabilities. For many natural hazards, the PDF can be determined based on past occurrences of the hazard. However, climate change can be expected to change the PDF of climate-related hazards. Under these conditions, the past may be a poor analog for the future. In order to achieve realistic risk estimates, including the uncertainties of these estimates, the potential change in the PDF of the climate-related hazards has to be kept in mind.

Assets can be anything from a building or service infrastructure, human population, and ecosystems to natural resources such as groundwater, fishing grounds, and beaches for tourist activities. Health services are also among the assets and so is the general state of public health in an area. Assigning value to the various assets in the coastal zone can be difficult. While the economic value of the built environment is relatively easy to determine, the value of human conditions and resources, human services, and ecosystem services is far more difficult to agree upon.

Assessing the vulnerability of assets also poses a wide range of challenges. For built structures, the vulnerability to natural hazards can be estimated based on knowledge of the materials' capacity to tolerate hazardous environmental conditions and the structural capacity to withstand environmental loads. Vulnerability of socioeconomic systems is far more difficult to assess, particularly if there are hidden thresholds that can lead to a collapse of the system. Likewise, determining vulnerability of ecosystems is difficult because of thresholds that are often not known. Vulnerability of health services to direct impacts of natural hazards and indirect impacts of the socioeconomic consequences of the hazards are difficult to quantify. The concept of resilience of these services to environmental, social, and economic disturbances can be an alternative to the risk-based approach.

1.03.3 Sea-Level Hazards

Coastal sea-level hazards include waves, currents, storm surges combined with tides, and slow inundation. These hazards can be exacerbated through slow changes in mean LSL. LSL is defined as the distance from the sea surface to the land surface. LSL changes whenever the sea surface height or the land surface height changes. At any coastal location, LSL is the result of many processes acting on local to global scales in space, and from instantaneous to millions of years in time. A complete overview of the processes impacting LSL is provided by Plag (2006) and Plag and Jules-Plag (2012).

In many coastal regions, the PDF of sea-level hazards can be determined based on long LSL records obtained by tide gauges (Tawn and Vassie 1989; Batstone et al. 2009), although multidecadal climate variability can lead to biased attributions (Donner 2102). Changes in the PDF of the sea-level hazards can result from two contributions: (1) the hazard (waves, currents, storm surges) itself may change in its frequency and intensity because of dynamic changes in the ocean/atmosphere system; and (2) the impact of the hazard may change because of a change in mean sea level. Figure 1 illustrates this interaction of slow, mediocre changes in mean conditions with possible changes in the extremes for the case of storm surges. With rising sea levels, storm surges will lead to increased and more frequent inundation of wetlands and lowlands, exacerbated coastal flooding, and eventually permanent submersion. LSLR will alter tidal ranges in rivers and bays, increase the heights of waves relative to land, and increase the salinity of estuaries and aquifers and impair water quality. Storm surges and waves will also erode shorelines more rapidly. LSLR will lead to changes in the locations where rivers deposit sediment and decrease the amount of light reaching the bottoms.

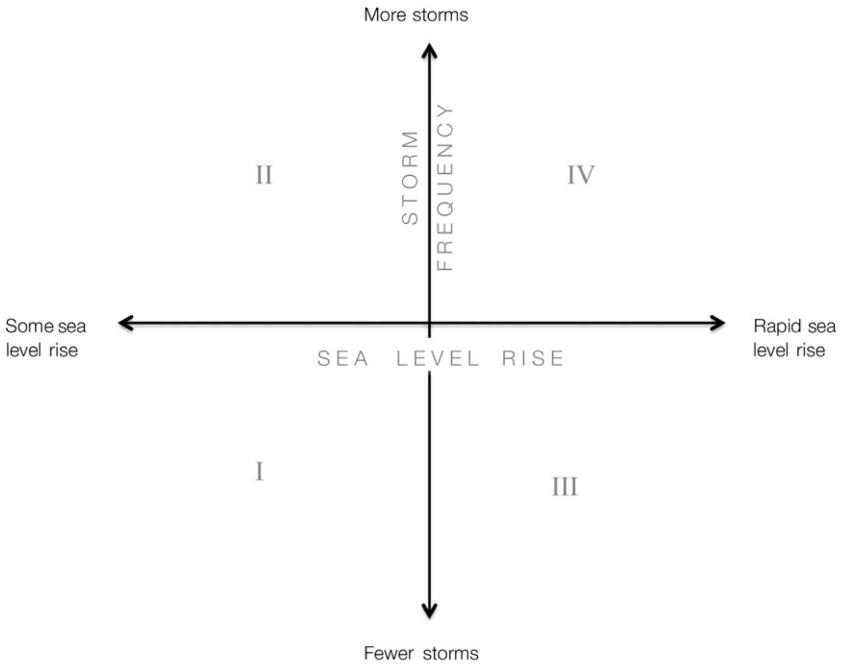

Figure 1 Impact of LSLR and storm surge frequency on hazard probability. A small LSLR and fewer storms (I) will not lead to any significant change in storm surge probability. However, even a small LSLR and more storms (II) would significantly increase the probability of a storm surge and inundation. Fewer storms combined with a rapid LSLR (III) would lead to less frequent but more intense storm surges and impact the higher end of the PDF. The most severe change in inundation risks result from more storms combined with a rapid LSLR (IV).

Considering the high sensitivity of the PDF of sea-level hazards to sea-level changes, it is mandatory to have an understanding of the PDF of LSL changes. Over the past two decades, an increasing number of GLSR and risk assessments have been carried out on national and international bases (e.g., Warrick and Oerlemans 1990; Warrick et al. 1996; Church et al. 2001; Hulme et al. 2002; Lowe and Gregory 2005; Anthoff et al. 2006; Plag et al. 2006; Tol et al. 2006; Rowley et al. 2007; Jacob 2007; CCSP 2008; Katsman et al. 2008, 2011). The large uncertainties in the plausible range of LSL trajectories and PDF resulting from these studies greatly reduce the value of these long-term assessments for risk management. A summary of these assessments shows that future LSL variations currently are not predictable on century timescales. Even with respect to the upper end of the range of plausible future LSL trajectories, large uncertainties exist, and recent scientific papers have sent an unclear and mixed message to decision makers and the public (see, e.g., the comments in the New York Times in 2008 and 2009 on recent papers such as Pfeffer et al. 2008; van de Wal et al. 2008; Rignot et al. 2008a; Blanchon et al. 2009; Hu et al. 2009; McPhee et al. 2009).

Following the Fourth Assessment Report of the Intergovernmental Panel on Climate Change (IPCC) (AR4), most of the recent assessments do not assume a significant future contribution from the ice sheets. Recent research has shown that dynamic links between climate and cryosphere are becoming more active (e.g., surface melt influence on ice sheet flow (Zwally et al. 2002), and ice dynamic response to ocean/ice interaction (Motyka et al. 2003; Holland et al. 2008)). Moreover, observed recent changes in the large ice sheets (e.g., Rignot et al. 2008a,b; Jiang et al. 2010; Jacob et al. 2012) as well as glaciers and ice caps (Meier et al. 2007; Pfeffer et al. 2008; Kierulf et al. 2009) indicate that an early onset of significant nonlinear responses of the cryosphere cannot be excluded, thus opening for a significant GSLR already over the next two to three decades. Current ice models cannot provide reliable long-term predictions of such a dynamic response (Lipscomb et al. 2009), and a major uncertainty for global sea-level (GSL) predictions is associated with the contribution from glaciers and ice sheets (see Plag and Jules-Plag 2012 for more details). There is also a potential for rapid GSLR not captured by any of the recent assessments, and the paleorecord may underestimate the maximum possible future rates. Over the past few centuries, humanity has reengineered the Earth in many aspects (e.g., atmospheric composition, land surface use, urbanization, water cycle, and biodiversity) and created states not encountered over the past few million years (see Section 1.03.3 Sea-Level Hazards in Plag and Jules-Plag 2012). The speed of changes in critical Earth system parameters is also unparalleled. Under these conditions, the response of the climate system may also exceed all rapid responses documented in the paleorecords. Thus, unparalleled sea-level change cannot be excluded.

The large uncertainties of any deterministic predictions and the existence of a low-probability, high-impact event (i.e., rapid LSLR) necessitate that risk-based planning considers the extreme event and aims to reduce the potential impact of such an event. The extreme sea-level event is a rapid rise combined with significant increases in storm intensity (area IV in Figure 1). Schwerzmann and Mehlorn (2009) conclude that for most of the countries around the Southern North Sea, climate change would lead to increased storms, and combined with LSLR, to increases in storm surge heights. Even a moderate LSLR limited to 37 cm (corresponding to the IPCC A2 estimate) would lead to an increase of between 36 and 55% in peak surge height compared to present-day levels. For the affected countries, these scenarios require systematic integration of the likely impacts of climate change into risk assessment and risk management processes.

1.03.4 The Assets and Their Vulnerability

As mentioned in the introduction, an increasingly large fraction of the human population is living in the coastal zone, often in urban areas. Air and water qualities have a significant impact on public health, and environmental changes in the coastal zone that negatively impact air and water qualities can have a significant impact on public health in the coastal zone and its hinterland. In many coastal zones, the local population depends on the rich coastal resources such as fishing grounds and mangroves. Healthy socioeconomic conditions are the basis for a healthy population. As discussed by Plag and Jules-Plag (2012), LSLR likely will degrade ecosystem services and thus impact both socioeconomic conditions and public health.

Urban areas host most of the advanced health service infrastructure, such as hospitals and laboratories. In coastal urban areas, this infrastructure is at risk from flooding during storm surges and slow degradations due to long-term effects.

Coastal LSLR can negatively impact health in many direct and indirect ways (Nicholls et al. 2007b; Craig 2010). **Table 1** summarizes the main groups of potential health impacts of LSLR and its associated effects. However, the vulnerability of public health also very much relates to the preparedness and socioeconomic status of communities from villages, towns, and cities to individual nations. For example, Bangladesh experiences only 1% of the world's cyclones but accounts for 50% of the deaths from cyclones worldwide (Khan et al. 2007). A large exposure to sea-level hazards combined with high socioeconomic vulnerability makes the population in the low-lying areas of Bangladesh particularly susceptible to adverse health impacts and threaten development achievements.

A main direct health impact of LSLR is associated with catastrophic flooding caused by storm surges. Coastal flooding has caused many deaths through drowning and other direct causes as well as many injuries. These floods also spread bacteria, viruses, and chemical contaminants. In the aftermath, flooding will foster the growth of fungi and contribute to the breeding of insects.

Flooding can cause environmental conditions leading to increased infectious diseases. Particularly, the spreading of vector-borne diseases, i.e., infections transmitted by the bite of infected arthropod species, such as mosquitoes, ticks, and triatomine bugs, and flies, such as sandflies and blackflies, can be promoted. Both permanent and intermittent flooding will allow vector-borne disease such as cholera and malaria to extend their ranges further inland. More frequent and intense flooding will also increase the number of occurrences and duration of exposure to pathogens. Rodent-borne disease, i.e., diseases carried by rats, mice, squirrels, or other rodents, can also be promoted by flooding because of altered patterns of human–pathogen–rodent contact.

The interruption of health services, energy supplies, communication, and transportation, and the reduced availability of health service staff tends to increase the direct impacts of the flooding. In many urban areas, flooding also results in severe water and air pollution, which will increase infectious and allergic diseases. The impact of Hurricane Katrina on New Orleans in 2005 illustrated the potential direct and indirect health impacts in developed areas of future similar disasters intensified by LSLR (Reible et al. 2006). This case also illustrates the long-term health effects from soil contaminations caused by the heavily polluted floodwaters. The Cyclon Sidr

Table 1 Vulnerability to and impacts of LSLR

Hazard or impact	*Direct health impacts*	*Health infrastructure*
Catastrophic coastal flooding	Deaths through drowning and other causes, injuries, infectious diseases (respiratory, intestinal, skin), mental health disorders	Health services interruption, availability of health staff, transportation disruption, energy and other supplies
Flood-induced pollution	Infectious diseases, allergies	Long-lasting degradation of health service infrastructure
Reduced water quality and reduced access to potable water due to salinification and/or pollution	Diarrheal diseases (giardia, cholera), hepatitis, other water borne diseases	Reduced water supply for health services
Impairment of food quality (through pollution of farmland and fisheries) and reduction of food supply (e.g., loss of farmland and decreasing productivity of fisheries)	Malnutrition; shellfish poisoning, marine bacteria proliferation	Food safety
Change in transmission intensity, distribution of vector-borne disease, abundance of vectors	Changes in malaria and other mosquito-borne infectious diseases	
Population displacements, degradation of livelihoods	Less well defined; can include increased social conflicts; increased crime rate; prostitution to replace lost income	General stress on health services because of rapid changes in demands

Modified from Nicholls, R. J., P. P. Wong, V. R. Burkett, J. O. Codignotto, J. E. Hay, R. F. McLean, S. Ragoonaden, and C. D. Woodroffe, 2007b: Coastal systems and low-lying areas. *Climate Change 2007: Impacts, Adaptation and Vulnerability. Contribution of Working Group II to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, M. L. Parry, O. F. Canziani, J. P. Palutikof, P. J. van der Linden, and C. Hanson, Eds., Cambridge University Press, Cambridge, UK, 315–356.

disaster, which hit Bangladesh in November 2007, underlines the multiple health threats resulting from the disruption of water and food supplies, dislocation of people in the areas affected by flooding and the resulting overcrowding in refugee areas, the combination of malnutrition and transmission of communicable disease, vector breeding, and poor access to health services (WHO 2007).

Indirectly, flooding can also lead to pollution of farmland and fisheries, with the consequence of degrading food quality. Polluted farm produce and fish can lead to slow degradation of human health, and increased events of shellfish poisoning can cause a higher death toll. A reduction in food supplies due to a loss of farmland through permanent inundation or erosion could increase malnutrition, particularly in regions of poverty.

The disruption of systems for sanitation, sewage disposal, and storm-water drainage would also have health implications. A reduction in water quality and in the supply of potable water due to pollution will increase the occurrence of cholera and other diarrheal diseases, as well as hepatitis and other water borne diseases. The cholera bacterium has a sea stage, during which copepods (type of zooplankton) act as host organisms (Colwell 2002). Between epidemics, the bacteria can survive with these hosts as an inactive but still infectious sporelike form. LSLR in connection with changes in sea temperature and currents could facilitate the spread of cholera (Colwell 2002), both directly and through contamination of drinking water.

Fish, shellfish, and sea mammals in the marine environment consume algae that are at the base of the marine food web. A reduction in these plankton feeders as a result of overfishing, water pollution, or disease may thus contribute to blooms of harmful algae. Plankton blooms can also harbor cholera and other bacteria, thus increasing health risk.

In combination with higher temperatures in many coastal zones, increased flooding will contribute to resurgence of mosquito-borne diseases, such as malaria, in some areas and the introduction of new mosquito-borne diseases, such as dengue fever, in others (see the reference in Craig 2010). Malaria is already found in areas where it was never found before.

The forced displacement of coastal communities through storm surges or permanent inundation, particularly in areas with limited resources, would further increase the risk of various infectious, psychological, and other diseases.

Although salt water intrusion can have a negative impact on the biodiversity and productivity of estuaries, its effects on public water supply are the most important consequences for public health. The most vulnerable coastal communities often depend on local sources of freshwater. These sources of coastal freshwater can be either surface sources, such as lakes and rivers, or groundwater aquifers accessed through wells. Both sources are vulnerable to salt water intrusion and salinification as a consequence of LSLR.

In coastal aquifers, fresh groundwater normally overlies saline water because freshwater is less dense than salt water. Although the dynamics impacting the interface between fresh and saline waters are complicated and depend on many parameters, a simple static approximation provides a rough estimate expressed by the Ghyben–Herzberg relation (see e.g., Barlow 2003): if h is the height of the groundwater table above sea level and z the depth below sea level of the interface between fresh and saline waters, then

$$z = \frac{\rho_{\mathrm{f}} \cdot h}{\rho_{\mathrm{s}} - \rho_{\mathrm{f}}}, \tag{1}$$

where ρ_{f} is the density of freshwater and ρ_{s} the density of the saline water.

For average freshwater and seawater densities, $z \approx 40h$. Thus, even in areas where the groundwater table is only a few meters above sea level, saline waters are confined to greater depths, and freshwater resources can be extracted for use by humans. Many coastal urban areas depend on water resources in coastal aquifers. However, if freshwater is extracted more rapidly than replenished by rain and inflow from inland aquifers, the groundwater table will fall and the interface between fresh and saline waters will rise. The impact on the interface between fresh and saline waters can be on the order of 40 times the fall in groundwater level. In many cases, water management authorities currently prevent salinification by releasing and recharging freshwater from reservoirs during droughts. Nevertheless, overextraction of groundwater is today the leading cause of salinification of coastal groundwater resources.

However, coastal groundwater resources are also impacted by salinification caused by LSLR (**Figure 2**). As LSL rises, low-lying coastal areas are inundated with saline waters. The height of the groundwater level relative to LSL changes over a wide zone, and this impacts the position of the interface between fresh and saline waters over a large area. This process can lead to a slow salinification of freshwater in wells further away from the inundated area. If not discovered, this slow salinification can have severe direct and indirect impacts on human health. Salinification of coastal aquifers is a long-lasting process. For example, the rapid LSLR of about 120 m at the end of the last glacial period led to salt water intrusions in many aquifers in Florida, where it continues to circulate today (Morrissey et al. 2008).

1.03.5 Risk Assessment

As summarized in Section 1.03.2 Risk-Based Approach to the Impact of Sea-Level Rise on Human Health, the LSLR-related health risk is the product of hazard probability, vulnerability of the assets in terms of health impacts, and the value of the assets exposed. In terms of hazard probability, the authors have outlined that there is a very high probability for a moderate GSLR, resulting in many coastal areas in a high probability for a twenty-first century LSLR on the order of 0.5 m or more. While it is difficult to assess the probability of an extreme LSLR of 2 m or more, such large values cannot be excluded.

Over the past few centuries, the assets exposed in the coastal zones have dramatically increased, and this tendency is likely going to continue. Coastal LSLR has the potential to impact on the order of 50% of all human assets. Vulnerability related to health is high because of several threats, including degradation of health services and infrastructure during flooding, reduced food and water security, increased exposure to disease, and increased pollution of water, air, and soils due to toxic materials and infrastructure inundated by seawater. A main vulnerability threatening public health may, however, not be in

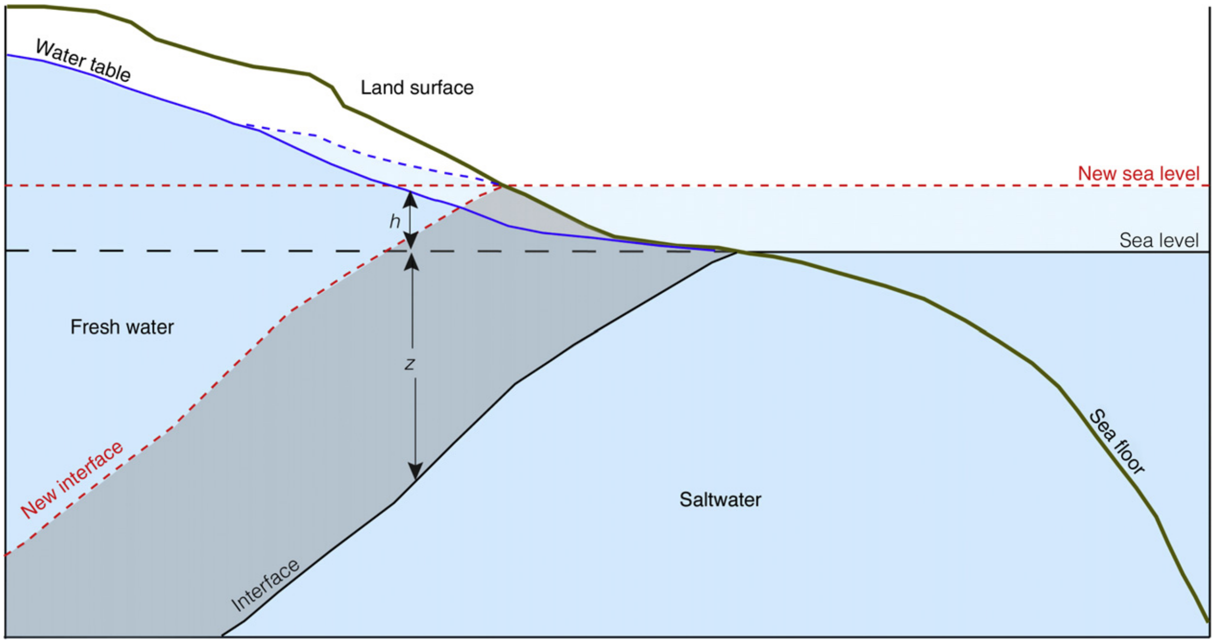

Figure 2 Impact of LSLR on groundwater resources. Depending on the coastal topography, even a small increase in sea level (broken lines) can significantly alter the interface between fresh and saline waters and lead to salinification of groundwater over a wide zone (shaded area). *h* is the height of the water table above sea level, and *z* the depth of the interface between fresh and saline waters below sea level. Modified from Barlow, P. M., 2003: *Ground Water in Fresh Water–Salt Water Environments of the Atlantic Coast, Circular 1262*. U.S. Geological Survey, Reston, Virginia.

the direct and indirect impacts listed here, but rather in the socioeconomic impacts. A significant GSLR and the increased frequency and magnitude of storm surges resulting from the associated LSLR would potentially have devastating impacts on coastal cities and settlements (e.g., Rowley et al. 2007; Edwards 2008), including a 'displacement through flooding and tropical storm activity of up to 332 million people in coastal and low-lying areas' (Watkins and HDR Team 2007). The societal and economic impacts would be felt globally. Loss estimates for single major disasters due to storm surges and hurricanes hitting urban coastal areas in the United States are in excess of $100 billion for the immediate damages (e.g., Chapman et al. 2006; Jacob 2007; Nicholls et al. 2007a). Even the slow increases in GSL projected by the IPCC AR4 (Meehl et al. 2007) would change the risks associated with storm surges and hurricanes in many coastal areas, potentially leading to extreme disasters in coastal areas with dense urban settlements. Regionally, LSLR can exceed the global average rise by 50% and more. A rapid LSLR over a few decades, which cannot be excluded scientifically, would amplify the risks and the ensuing disasters, and it would reduce the time for adaptation.

Consequently, our civilization is challenged by a high health risk associated with LSLR. A detailed quantification of this risk would have to take into account several scenarios for LSLR. For example, if the main source of GSLR would be a rapid melting of parts of the Greenland ice sheet, then the Southern Hemisphere would experience a larger than average LSLR, with severe consequences for the coasts of Africa, South America, Australia, and Southern Asia, while many coastal areas in the Northern Hemisphere would experience lower than average LSLR, and at coastal zones closer to Greenland even an LSL fall. If the main source would be a melting of a part of Antarctica, we would experience the reversed geographical pattern, with a significantly different regional and global risk. If both large ice sheets contribute, the higher latitudes would have lower than average rates, while the lower latitudes would experience the main impact with a larger than average LSLR.

Taking into account the high costs of adaptation and of potential disasters caused by coastal hazards, both over- and underprotection and adaptation can be very costly and can significantly impact national economies. Adaptation may require relocation of settlements (e.g., Vellinga 2007) and major infrastructure, including railroads, highways, and airports (see, e.g., CCSP 2008). Already the projected relatively moderate GSLR puts large numbers of people in vulnerable locations. Complete and partial relocation of populations living in severely affected areas such as Tuvalu, Bangladesh, and Samoa is already creating climate change refugees. Other areas where populations may need to be relocated include the Maldives, Guyana, and the Netherlands. If adaptation, including relocation of people and infrastructure, is delayed and a GSLR as projected or larger happens, large numbers of environmental refugees are likely to result, and inundated infrastructure is likely to cause considerable pollution and environmental impacts. Thus, policy and decision makers are faced with a trade-off between investing today large amounts in coastal protection and adaptation or loading the large human and economic costs of potential disasters on future generations.

Considering the extent of assets at risk in the coastal zone, any significant GSLR will challenge the global society at an unparalleled scale. Therefore, this risk, no matter how low the probability of a GSLR is, cannot be ignored. As pointed out by

Craig (2010), an adaptive management based on a public health approach may be the most suitable approach to address this risk of LSLR.

1.03.6 Conclusions

The risk of a rapid and large LSLR is real for many coastal areas, and even a slow and moderate LSLR has the potential to cause significant changes in storm surge intensity, with severe threats for human health. Reducing the risk associated with LSLR poses two challenges for policy and decision makers trying to formulate adaptation plans: (1) Even a rapid LSLR will seldom exceed a few centimeters per year and will be perceived as slow. Therefore, even in the worst case, realizing climate change-driven LSLR will take decades, and will often be obvious only during storm surges. (2) Predictions of GSLR are highly uncertain, and there is a nonzero probability that the actual GSLR will be outside the projected range of plausible trajectories.

The analysis by Lonsdale et al. (2008) for London shows that extreme scenarios could be highly challenging, even for areas with well-developed institutions. As in the case of London, experts and decision makers are often polarized between two extreme options to reduce the risk: (1) reconfiguring the urban area around the rising sea and (2) building new barriers that would allow the urban areas to continue as today. In many coastal areas, this lack of consensus has the potential for paralysis in response to the low-probability, high-impact extreme LSLR. In the case of rapid LSLR, it could lead to an unplanned response as the existing defense capabilities are overwhelmed. Hence, any extreme, low-probability, high-impact LSLR will likely challenge the existing institutions. Adaptive management is presented by Lonsdale et al. (2008) as an approach to address this challenge. Adaptive management has the ability to react to new information concerning the magnitude and speed of LSLR as that information becomes available. It also helps decision makers not to be overwhelmed by the scientific uncertainties about the trajectory of future LSLs (Craig 2010).

Adaptive management addresses core concerns, which will lead to improvements no matter how LSL is going to change, and at the same time will reduce the risk of disasters if LSL rises significantly. The core concerns for coastal areas identified in the previous sections relate to (1) the availability of potable water; (2) the potential for toxic contamination of water, air, and soil as seawater inundates coastal areas; and (3) potential changes in the exposure to diseases. The first requires drinking water supplies based on resources less prone to salinification, and to reduce other pollution threats for these resources. The second may necessitate changes in land use in the coastal zone and the removal of toxic material and infrastructure from potential inundation areas in the coastal zone. The third might lead to changes in health services and training needs. In each of these areas of core concerns, governments and planners can identify adaptation measures that can be implemented immediately, which will increase resilience and be beneficial to coastal communities independent of the actual impacts of LSLR on these communities.

In the absence of actionable century-scale GSL and LSL predictions, recently, several city managers have indicated that 'early warnings' for a rapid LSL rise with lead times of 5–15 years would provide actionable information for decision makers (e.g., T. Reeder 2009, personal communication). Such short lead times require a continuously operating LSL forecasting on decadal timescales (e.g., Plag et al. 2010). To a certain extent, such a service would be comparable to the ongoing sky watch for near-Earth objects, which aims to provide early detection of the low-probability/high-risk event of a large object approaching Earth. The development of policies and mitigation and adaptation strategies for resilient coastal areas would benefit from an LSL service that combines continuous observations of key components of the Earth system (such as the ice sheets, ice caps, and major glaciers; ocean currents; ocean temperature; land water storage; sea surface height changes; and vertical land motion) with models that assimilate these observations and forecast short-term (years) and intermediate (decades) LSL changes. Such a service is required in order to facilitate adaptive management where and when necessary. Of particular importance is the continuous monitoring of the large ice masses in order to identify any ice masses that enter a state of instability. For these masses, predictions of their disintegration trajectories will be possible. On the basis of such disintegration predictions, LSL can be forecast with the same time horizon as for the ice sheets if a validated ice–ocean–solid-Earth model is available. Likewise, ocean observations will be able to detect the onset of major changes in ocean circulation and heat content affecting GSL and LSL, and validated atmosphere–ocean models will be able to forecast further development on decadal timescales. Living on a reengineered planet with potentially unprecedented rapid changes requires a well-developed monitoring and predictive system to inform decision makers in a timely manner about any pending extreme events.

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1.04 Impact of Environmental Change on Ecosystem Services and Human Well-being in Africa

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Glossary

Desertification land degradation caused by climate and human activities.

Drought a temporary lack of water caused primarily by climate, which negatively affects the environment and human society.

Environmental change the biophysical transformation of land, water, and the atmosphere as a result of both natural processes and human activities.

Ecosystem services the benefits from ecosystems that enable humans to survive and that support their quality of life.

Human well-being a multidimensional concept encompassing all aspects of human experiences including the environment, health, education, social relations, livelihood opportunities, security politics, and governance.

NDVI Normalized Difference Vegetation Index derived from satellite-borne instruments is a numerical indicator of vegetation greenness, which can be compared across different images.

1.04.1 Introduction

Environmental change describes the biophysical transformation of land, water, and atmosphere as a result of both natural processes and human activities (von Falkenhayn et al. 2011). It occurs at a range of scales from local to global and affects the social and economic well-being of human society, primarily through its impact on ecosystem service provision. Such services can be described as the benefits from ecosystems that enable humans to survive and that support their quality of life (Harrington et al. 2010) (Table 1). They include provisioning services such as food and water, regulating services derived from the interaction of biotic and abiotic elements, cultural services, and supporting services such as primary production and nutrient cycling (MA 2005). Although pathways are incompletely understood, ecosystem services are strongly linked to human well-being (Butler et al. 2005) through their general influence on people's safety and

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Table 1 The main ecosystem services (with selected examples) provided by the environment for human society as well as the human well-being criteria necessary for a good quality of life, based on the conceptual framework and terminology developed by the Millennium Ecosystem Assessment (MA 2005)

Ecosystem services	*Human well-being*
Provisioning (food, water, fuel wood)	Security (personal safety, secure resource access, security from disasters)
Regulating (climate, water)	Basic material for good life (food, shelter, adequate livelihood)
Cultural (spiritual, recreational)	Health (strength, feeling well, access to clean water)
Supporting (primary production, nutrient cycling)	Good social relations (social cohesion, mutual respect)
	Freedom of choice and action (opportunity to be able to achieve what an individual values doing and being)

MA, 2005: Ecosystems and human well-being: current state and trends. Hassan, R., R. Scholes, and N. Ash, Eds., Findings of the Condition and Trends Working Group, [Available online at http://www.millenniumassessment.org/en/index.aspx.]

access to basic resources, including food and shelter, which in turn affects people's health and the societies in which they live. Ultimately human well-being is determined by the choices that people make and their opportunities in life.

We focus initially on the impact of direct drivers on African environments (Figure 1). These include natural processes such as climate and drought, as well as those resulting from human activities such as land use, land cover change, and invasive species introductions. The authors first describe the extent, nature, and rate of change that has occurred in African environments in response to each of these pressures with an emphasis on the Sahel, eastern and southern African regions. The role of indirect drivers such as society and politics or demographic shifts, which are often influenced by policy or management decisions, or individual responses such as mobility and migration, are also discussed in terms of their impact on environmental states. Next, how these changes have affected ecosystem service provision and human well-being is discussed. Although indirect drivers and people's responses clearly impact strongly on human well-being, a thorough discussion of these interactions is beyond the scope of this review. Finally, the authors document historical trajectories and explore some of the counter narratives of environmental change and its potential impact in Africa.

This contribution adds to the rapid recent awareness of the full role that humans have played in global environmental change. It draws on the work of the International Human Dimensions Programme on Global Environmental Change (Von Falkenhayn et al. 2011) as well as the Millennium Ecosystem Assessment initiative (MA 2005). The comprehensive synthesis undertaken by Scholes and Biggs (2004) for sub-Saharan Africa has particular relevance, in addition to UNEP's Africa Environment Outlook (UNEP 2006) and their Encyclopedia of Earth initiative (www.eoearth.org).

1.04.2 Environmental and Social Circumstances in Africa

Africa straddles the hemispheres, is more than 8000 km long and 7500 km wide, and covers about 30 million km^2 or one-fifth of the world's total land area. The continent possesses high seasonal, annual, and decadal variability in its climate, which is influenced by a number of large-scale, intra- and interhemispheric climatic processes and weather systems. These include the circumpolar westerlies, the West African Monsoon, the Intertropical Convergence Zone (ITCZ), and the El Niño–Southern Oscillation. Sea surface temperatures (SSTs) appear to have a particularly important influence on decadal scale variability in Africa's climate (Mohino et al. 2011).

The continent is dominated by woodlands, shrublands, and grasslands, which comprise 42% of Africa's land surface (Mayaux et al. 2004) (Figure 2; Table 2). Agriculture occurs on about 12% of the continent, while a third of Africa's land surface is comprised of bare soil. Although anthropogenic impacts such as herbivory and fire do have an important influence on vegetation type and cover at local scales (Bond 2008), natural environmental factors, particularly annual precipitation (Figure 3), are excellent predictors of the distribution of vegetation in Africa, especially that of forest and bare soil cover (Greve et al. 2011).

In 2010, about 1 billion people, or 15% of the world's population, lived in Africa. Between 2005 and 2010, Africa's population grew at 2.3% and is expected to rise to between 1.93 and 2.47 billion people by 2050, contributing more than half of the increase expected in the world's population. Africa's high infant mortality rate of 96 deaths in 1000 and relatively low life expectancy of 55.2 years are the worst human health indicators of any continent (United Nations 2011).

Africa's annual per capita gross domestic product (GDP) in 2009 was US$2005 (United Nations 2011), or about 7% of that of countries with high human development. Overall, 78% of the continent's population lives on less than US$2 a day (UNEP 2010) and 330 million sub-Saharan Africans live in extreme poverty (Hellmuth et al. 2007). Such statistics hide the considerable variation in poverty levels between different regions and countries and also between people living in urban and rural settings. With a current rate of urbanization of 3.5%, more than 53% of Africa's population is expected to live in urban areas by 2030 (UNEP 2010).

The economies of many African countries are strongly reliant on their agricultural base, (UNECA 2008) and the amount of rain, or lack thereof, can have a significant influence on the national GDP (Hellmuth et al. 2007). While over 56% of Africa's labor force is employed within the agricultural sector, more than 90% of rural Africans are engaged in some form of agricultural activity (UNEP 2010). Although agricultural production has declined in recent years, it represented 20–30% of sub-Saharan Africa's GDP and 55% of its exports at the end of the twentieth century (Elasha et al. 2006). Despite the high level of involvement of Africa's population in agricultural activities, the continent spends up to US$20 000 million each

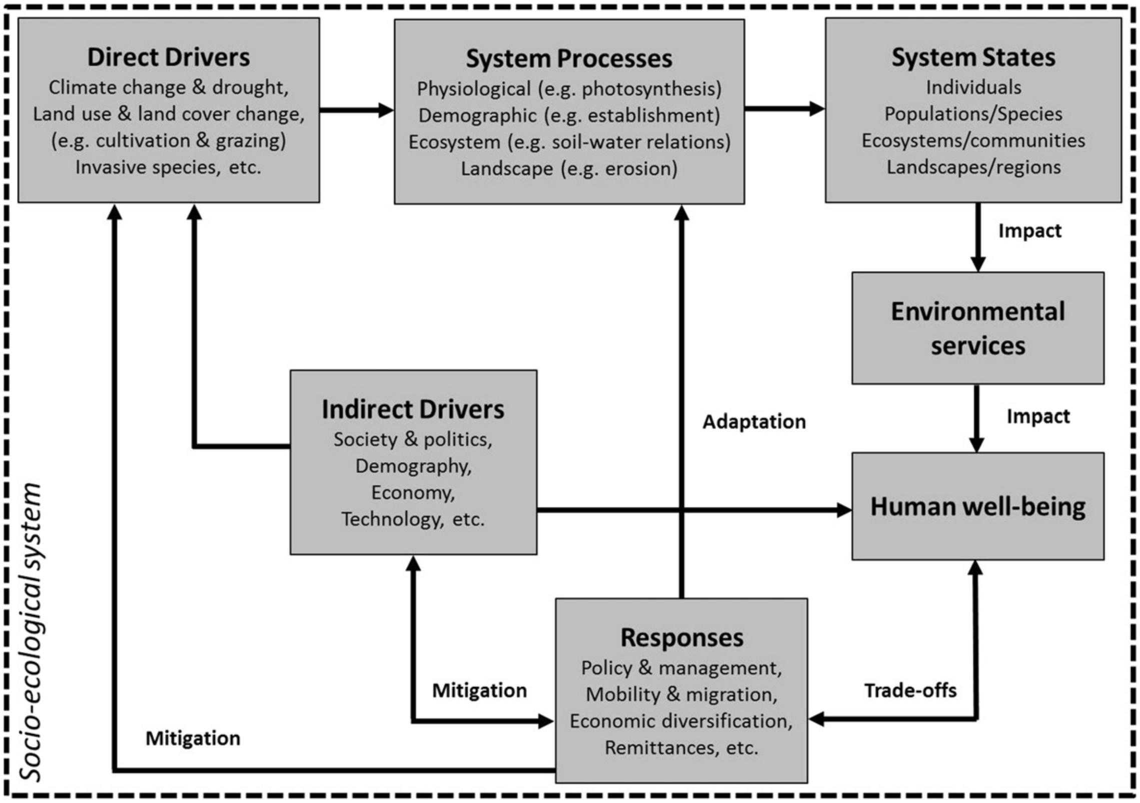

Direct Drivers
Climate change & drought,
Land use & land cover change,
(e.g. cultivation & grazing)
Invasive species, etc.
System Processes
Physiological (e.g. photosynthesis)
Demographic (e.g. establishment)
Ecosystem (e.g. soil-water relations)
Landscape (e.g. erosion)
System States
Individuals
Populations/Species
Ecosystems/communities
Landscapes/regions
Impact
Environmental services
Impact
Indirect Drivers
Society & politics,
Demography,
Economy,
Technology, etc.
Adaptation
Human well-being
Responses
Policy & management,
Mobility & migration,
Economic diversification,
Remittances, etc.
Mitigation
Trade-offs
Mitigation
Socio-ecological system

Figure 1 A framework of understanding the impact of environmental change on environmental or ecosystem service provision and human well-being within a broadly constituted socioecological system. Based on the conceptual models of Rounsevell, M. D. A., T. P. Dawson, and P. A. Harrison, 2010: A conceptual framework to assess the effects of environmental change on ecosystem services. *Biodivers. Conserv.*, **19,** 2823–2842 and Prober S. M., and Coauthors, 2012: Facilitating adaptation of biodiversity to climate change: a conceptual framework applied to the world's largest Mediterranean-climate woodland. *Clim. Change*, **110,** 227–248.

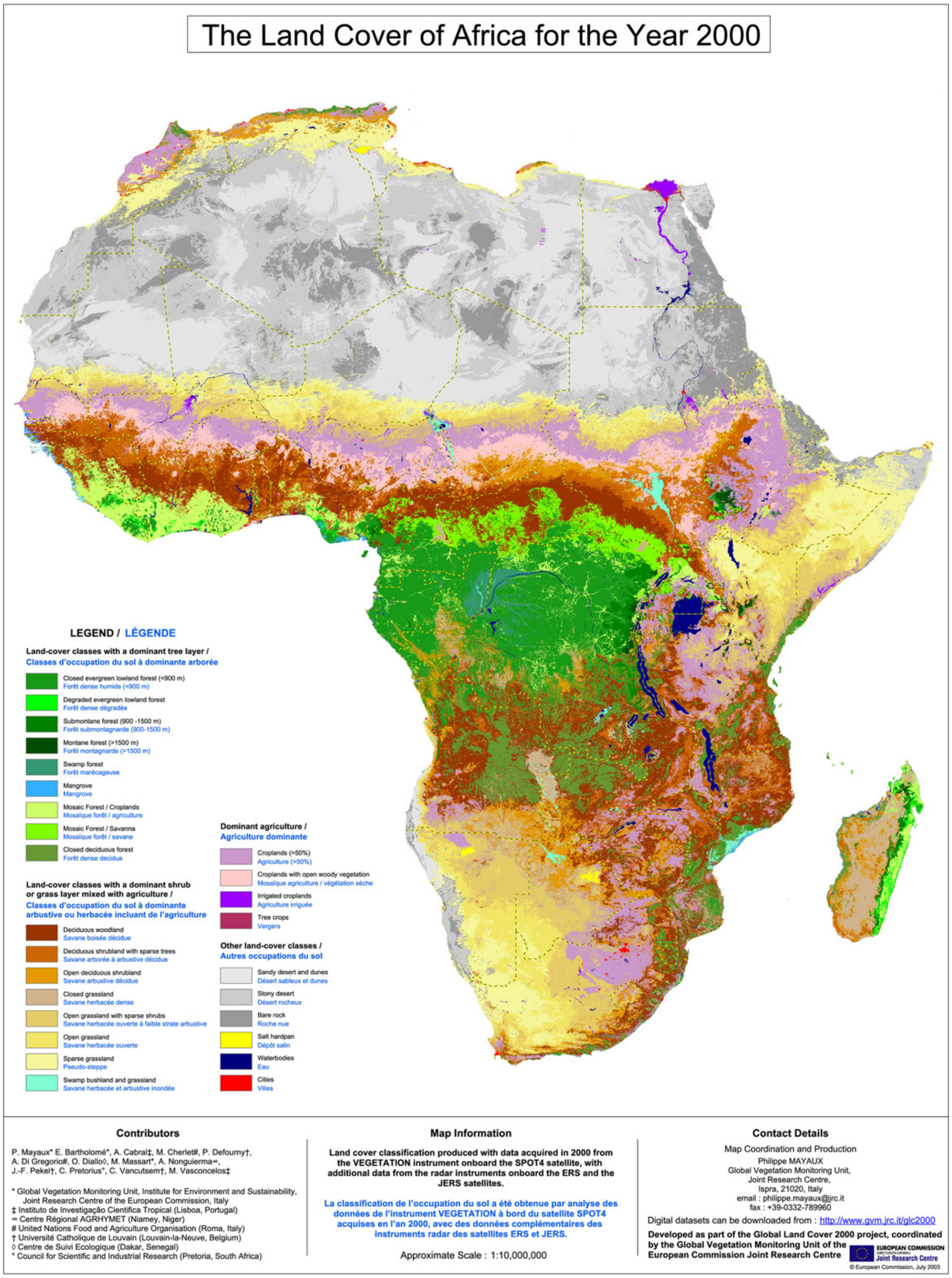
year on food imports, in addition to the US$2000 million it receives annually in food aid (UNEP 2010). Approximately half the World Food Aid Programme's annual budget is spent on food aid to the continent (UNECA 2008). Even so, the Food and Agricultural Organisation estimated that in 2009, 265 million people in sub-Saharan Africa were suffering from chronic hunger, while undernutrition causes 1.7 million deaths in Africa every year (Ramin and McMichael 2009).

1.04.3 The Impact of Drought in Africa

1.04.3.1 Climate Variability Over Longer Timescales

Paleoclimatic reconstructions of Quaternary environments for northern Africa indicate that glacial periods have generally been arid, while the interglacials have been more humid (Brooks 2004). There is considerable variability, however, on millennial and centennial timescales. For example, the first half of the Holocene, from about 9000 to 4000 years BP was significantly wetter than at present (Lézine et al. 2011), and the region contained a series of interlinked waterways formed by a large interconnected series of rivers, lakes, and inland deltas (Drake et al. 2011). During this period, known as the African Human Period (deMenocal et al. 2000), significantly more areas of the Sahara Desert were dominated by semiarid tropical savanna vegetation than at present (Watrin et al. 2009). This early Holocene humid phase facilitated the dispersal of humans across northern Africa into areas that are uninhabitable today (Drake et al. 2011). Whether rapid and nonlinear (Brooks 2004) or gradual and progressive (Kropelin et al. 2008), a spatially variable aridification phase started about 5500 years BP (Lézine et al. 2011). This resulted in a decrease in vegetation cover and a contraction of species associated with more humid environments leading to the present-day desertlike conditions, which were already established around 2700 years BP (Kropelin et al. 2008). The last millennium was characterized by repeated wetter and drier phases, sometimes of greater magnitude than anything experienced in the region in the last 100 years (Shanahan et al. 2009).

Environmental indicators and proxy measures derived from endoreic lake levels, pollen cores, and fluvial sediments suggest that eastern Africa has experienced cycles of aridity, degradation, and stability during the Holocene (Marshall et al. 2011). As for northern Africa, Nyssen et al. (2004) describe a cold and dry late Pleistocene (20 000–12 000 years BP), a wetter early Holocene (11 500–4800 BP), and then a shift to more arid as well as more erosive conditions after this period. Although there is temporal and spatial variability, a general warming trend over the last 350 years is evident for eastern Africa (Kiage and Liu 2009; Thompson et al. 2009). Extreme drought conditions have also been documented for western Uganda and central Kenya about 200 years ago as a result of a subcontinental scale reduction in rainfall at this time (Bessems et al. 2008).


The Land Cover of Africa for the Year 2000
LEGEND / LÉGENDE
Land-cover classes with a dominant tree layer / Classes d'occupation du sol à dominante arborée
Closed evergreen lowland forest (<900 m) Forêt dense humide (<900 m)
Degraded evergreen lowland forest Forêt dense dégradée
Submontane forest (900 -1500 m) Forêt submontagnarde (900-1500 m)
Montane forest (>1500 m) Forêt montagnarde (>1500 m)
Swamp forest Forêt marécageuse
Mangrove Mangrove
Mosaic Forest / Croplands Mosaïque forêt / agriculture
Mosaic Forest / Savanna Mosaïque forêt / savane
Closed deciduous forest Forêt dense decidue
Land-cover classes with a dominant shrub or grass layer mixed with agriculture / Classes d'occupation du sol à dominante arbustive ou herbacée incluant de l'agriculture
Deciduous woodland Savane boisée décidue
Deciduous shrubland with sparse trees Savane arborée à arbustive décidue
Open deciduous shrubland Savane arbustive décidue
Closed grassland Savane herbacée dense
Open grassland with sparse shrubs Savane herbacée ouverte à faible strate arbustive
Open grassland Savane herbacée ouverte
Sparse grassland Pseudo-steppe
Swamp bushland and grassland Savane herbacée et arbustive inondée
Dominant agriculture / Agriculture dominante
Croplands (>50%) Agriculture (>50%)
Croplands with open woody vegetation Mosaïque agriculture / végétation sèche
Irrigated croplands Agriculture irriguée
Tree crops Vergers
Other land-cover classes / Autres occupations du sol
Sandy desert and dunes Désert sableux et dunes
Stony desert Désert rocheux
Bare rock Roche nue
Salt hardpan Dépôt salin
Waterbodies Eau
Cities Villes
Contributors
Map Information
Contact Details
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Land cover classification produced with data acquired in 2000 from the VEGETATION instrument onboard the SPOT4 satellite, with additional data from the radar instruments onboard the ERS and the JERS satellites.

La classification de l'occupation du sol a été obtenue par analyse des données de l'instrument VEGETATION à bord du satellite SPOT4 acquises en l'an 2000, avec des données complémentaires des instruments radar des satellites ERS et JERS.

Approximate Scale : 1:10,000,000

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Digital datasets can be downloaded from : http://www.gvm.jrc.it/glc2000

Developed as part of the Global Land Cover 2000 project, coordinated by the Global Vegetation Monitoring Unit of the European Commission Joint Research Centre

Figure 2 Land cover in Africa in 2000. Mayaux, P., E. Bartholomé, M. Massart, C. Van Cutsem, A. Cabral, A. Nonguierma, O. Diallo, C. Pretorius, M. Thompson, M. Cherlet, J-F. Pekel, P. Defourny, M. Vasconcelos, A. Di Gregorio, S. Fritz, G. De Grandi, C. Elvidge, P. Vogt, A. Belward, 2003: *A land cover map of Africa*. Joint Research Centre, European Commission, Luxembourg. EUR 20665 EN. ISBN 92-894-5370-2 [Available online at http://bioval.jrc.ec.europa.eu/products/glc2000/products/Africa_posterA0.jpg.]

Southern Africa appears to have experienced periods of rapid warming and cooling during the Holocene, which are generally in phase with those for northern and eastern Africa (Scott et al. 2008; Chase et al. 2010). For example, in Namibia, evidence from fossil hyrax middens suggests fluctuating phases of relatively humid conditions from 8700 to 3500 years BP after which a period of marked aridity developed, lasting until 300 years BP (Chase et al. 2009). While centennial and

Table 2 The area of Africa's land cover classes (in square kilometers) (excluding Madagascar) based primarily on vegetation structure

Region	*Dense forest*	*Mosaic forest/other*	*Woodlands*	*Shrublands*	*Grasslands*	*Agriculture*	*Bare soil*	*Wet lands*
North Africa	5	0	45	130	458	167	5109	10
West Africa	104	476	503	653	819	965	2352	27
Central Africa	2034	541	940	542	163	350	702	25
East Africa	72	151	552	863	1601	1316	1589	45
Southern Africa	90	7	2041	1454	1560	672	187	60
Africa total	2304	1175	4080	3643	4601	3469	9939	167
Percentage	7.8	4.0	13.9	12.4	15.7	11.8	33.8	0.6

Compiled from Table 4 in Mayaux P., E. Bartholomé, S. Fritz, and A. Belward, 2004: A new land-cover map of Africa for the year 2000. *J. Biogeogr.*, **31**, 861–877.

millennial-scale suborbital events and variations in solar activity appear responsible for some of the fluctuations in southern African climate, these patterns are most strongly correlated with the relatively predictable change in high-latitude, Northern Hemisphere summer insolation cycles driven primarily by orbital precession (Chase et al. 2009, 2010). It is within these long-term changes in African climates that events of the twentieth century should be interpreted.

1.04.3.2 The Incidence of Drought in Africa in the Twentieth Century

1.04.3.2.1 Spatial Variability of Drought in Africa

Droughts can be conceived of as a temporary lack of water caused primarily by climate, which negatively affects the environment and human society (Kallis 2008). Because Africa comprises extensive arid and semiarid areas with unpredictable rainfall, the incidence of drought is high (UNECA 2008; Dai 2011a). It has had a devastating impact on African environments and societies for millennia (Touchan et al. 2011), particularly in the Sahel and Greater Horn of Africa (GHA) regions. Relative to the wide-scale loss of life and social disruption that accompanied the Sahelian droughts of 1968–74 (Batterbury and Warren 2001) or the most recent 2010–2011 drought in the GHA region (Loewenberg 2011), the impact of drought in southern Africa in the twentieth century has been largely agricultural and economic, rather than social and life-threatening (Benson and Clay 1998; UNECA 2008).

1.04.3.2.2 Case Study: The 1968–1974 Drought in The Sahel

Environmental Collapse in the Sahel

The Sahel stretches over 5000 km across the width of Africa roughly between 10 and 20°N in a broad transition zone between the arid Sahara desert in the north and the more mesic

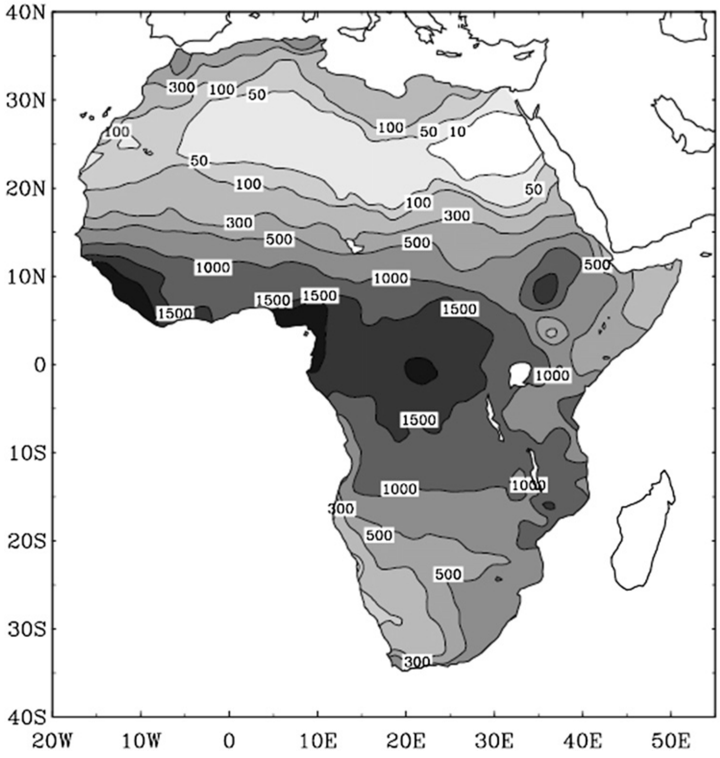

Figure 3 Mean annual rainfall (in millimeters) for Africa. From Nicholson, S., 2001: Climatic and environmental change in Africa during the last two centuries. *Clim. Change*, **17**, 123–144.

savanna environments in the south. The 200- and 600-mm rainfall isohyets provide the conventional climate bounds of the region (Hein et al. 2011). Because of its geographic position and relatively high population densities, the Sahel is vulnerable to both climate and land-use impacts (Hein 2006). In addition to the high interannual variability in rainfall, the region is also characterized by spatially coherent, decadal scale fluctuations in rainfall amounts (Caminade and Terray 2010). The first part of the twentieth century and particularly the 1950s were relatively wet, while a series of devastating droughts were experienced in the region from the late 1960s to the early 1990s (Nicholson 1993) (**Figure 4**). The extent and severity of this sustained 20–30% decline in rainfall was unprecedented in the observational record not just for the Sahel but also for anywhere on Earth (Hulme et al. 2001).

These droughts had a significant effect on the vegetation of the region. In an extensive 11-month field study in 1993–1994 undertaken along a 1900-km transect in Senegal in the western Sahel, Gonzalez (2001) documented the long-term changes in forest vegetation of the Sahel, Sudan, and Guinean vegetation zones in response to the extended Sahelian droughts of the 1970s and 1980s. He used a combination of field surveys, participatory mapping, and aerial photograph analysis and showed that from 1945 to 1993, the Guinea and Sudan vegetation zones had contracted southwest at an average rate of 500–600 m year^{-1} (**Figure 5**). Average species richness within areas of 4 km^2 declined by about a third from 64 to 43 species with the more mesic Guinean tree and shrub species most affected. From the aerial photographic analysis, he documented a 22% decrease (from 10 to 7.8 trees per hectare) in the density of trees >3 m in height. Traditional firewood species had also declined as had useful medicinal plants and those species that provided fruits, leaves, and gum during drought emergencies. He concluded that the region had 'lost its capacity' to support current population densities and would be unable to do so under future drought conditions.

Climatic Determinants of Sahelian Drought

Gonzalez (2001) showed that changes in rainfall and temperature over the study period best explained the changes in tree richness, density, and distribution and that a change in SST appeared partially responsible for the reduction in rainfall. Subsequent research has shown that variability in twentieth century Sahelian precipitation is strongly influenced by SST in the Atlantic and Indian Oceans (Giannini et al. 2003; Huber and Fensholt 2011; Williams and Funk 2011; Wolff et al. 2011) as well as teleconnections involving the El Niño–Southern Oscillation (ENSO) phenomenon in the Pacific Ocean (Caminade and Terray 2010). Using a general circulation model (GCM) Mohino et al. (2011) explored the relative contribution of these potentially competing atmospheric components to the variability in twentieth century Sahelian precipitation. They found that decadal, multidecadal and long-term trends in SSTs in the Atlantic, Indian, and Pacific Oceans explained most of the variability in rainfall. For example, 50% of the droughts in the 1980s could be explained by the Atlantic Multidecadal Oscillation (AMO), 40% by the interdecadal Pacific Oscillation (IPO), and 10% by the long-term global warming trend in the tropical Indo-Pacific and Tropical Atlantic Oceans. Mohino et al. (2011) provide mechanistic explanations for these impacts including patterns of subsidence and shifts of the ITCZ in response to different atmospheric influences. They also partition the contribution of each component to the mid-1990s partial recovery in rainfall in the Sahel (**Figure 4**), which they suggest was largely driven (80%) by the AMO.

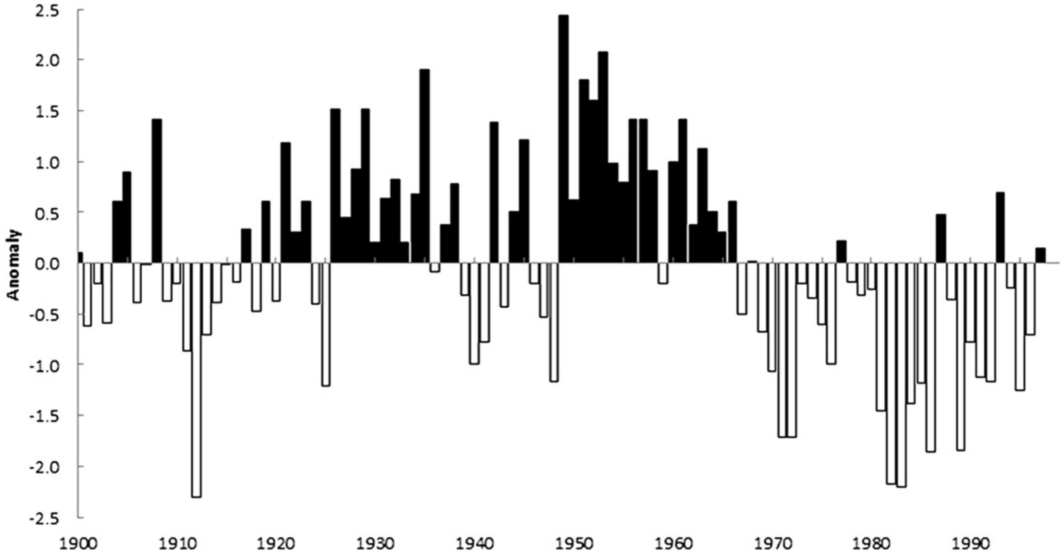

Figure 4 Anomalies (+SD) relative to the long-term mean in spatially aggregated annual rainfall for the Sahelian zone for the period 1901–98. Redrawn from Brooks, N. 2004: Drought in the African Sahel: long term perspectives and future prospects. Tyndall Centre for Climate Change Research Working Paper No. 61, 1–37. [Available online at http://www.tyndall.ac.uk/sites/default/files/wp61.pdf. Accessed 21 December 2011.] based on the data set of New M. G., M. Hulme, and P. D. Jones, 2000: Representing 20th century space-time climate variability. Part II: development of 1901–1996 monthly terrestrial climate fields. *J. Clim.*, **3,** 2217–2238.

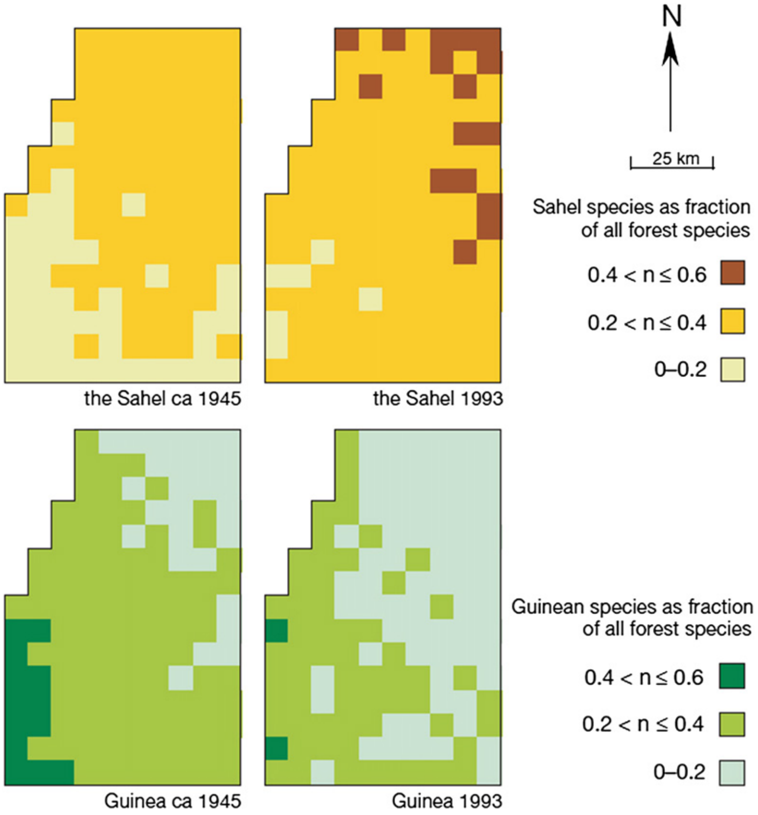

Figure 5 Shift of the Sahel and Guinean vegetation zones in Northwest Senegal (15° 00′ to 16° 01′ N, 16° 00′ to 16° 42′ W) from *c.* 1945 to 1993. From Gonzalez, P., 2001: Desertification and a shift of forest species in the West African Sahel. *Clim. Res.*, **17,** 217–228.

Anthropogenic Determinants of Sahelian Drought

Gonzalez (2001) and others (e.g., Sinclair and Fryxell 1985; Miehe et al. 2010) have also highlighted the potential influence that anthropogenic impacts could have had on regional weather patterns as a result of large-scale transformation of the Sahel's vegetation cover and the associated effect that this might have on the hydrological cycle and land–atmospheric processes (Los et al. 2006). However, many remote-sensing studies suggest that land-use impacts are not immediately evident at large spatial scales. For example, Seaquist et al. (2009) used the National Oceanic and Atmospheric Administration's (NOAA) advanced very high resolution radiometer (AVHRR) Normalized Difference Vegetation Index (NDVI) for the period 1982–2002 and compared composite NDVI values with modeled values predicted by the Lund Potsdam Jena-Dynamic Global Vegetation Model (LPJ-DGVM) for the same period. Differences in the output for each cell were then related to a land use and population pressure data set and assessed in terms of the potential impact of people on vegetation greenness. Like Hickler et al. (2005), Herrmann et al. (2005), and Fensholt and Rasmussen (2011), their results provided no evidence that livestock production has significantly affected the broad-scale vegetation dynamics of the region over the period of study, although pasture production might have positively influenced NDVI scores. However, the effects of negative local-level impacts on vegetation greenness, which are not detectable by satellites, are emphasized. Hein et al. (2011) suggest more generally that further work is necessary to determine the anthropogenic effects of land use on Sahelian environments as measured from satellite-borne instruments. They caution against accepting too uncritically the view that twentieth century land-use practices have not had a significant negative effect on Sahelian environments (Hellden 1988). Land degradation clearly occurs as a result of a multiplicity of factors, and it is often difficult to isolate individual causative factors such as a particular land-use practice (Mbow et al. 2008).

1.04.3.3 The Impact of Drought in Africa

1.04.3.3.1 Drought Impact in the Sahel

The widespread and extensive drought between 1968 and 1974, in particular, led to an unprecedented environmental emergency and humanitarian crisis in the region and severe economic hardship for the people of the Sahel (Berg 1976; UNECA 2008). It was a major 'historical marker' (Batterbury and Warren 2001) and propelled the issue of land degradation onto the world stage, beginning a number of global initiatives such as the World Meteorological Organisation (WMO) expert missions in the region in 1972 (Sivakumar et al. 2011) and the United Nations Conference on Desertification (UNCOD) in 1977 (Herrmann et al. 2005).

While several statements exist of the 'hundreds of thousands of people' who died and the 'millions of animals' (UNEP 2004; UNECA 2008) that perished in the 1968–1974 Sahel drought, surprisingly few analyses of the impact of this drought on human well-being have been published. The most important is probably that of Berg (1976) whose findings focused both on the 'irreversible' effects of the drought, such as loss of life, extended periods of malnutrition, and environmental transformation, as well as on the 'reversible' effects such as the decline in agricultural output and the balance of payments. Malnutrition and hunger were certainly widespread as evidenced by the fact that in 1974, as many as 750 000 people were directly dependent on food aid (UNEP 2004). Data for cattle losses suggests that as many as a third of the animals perished in the drought. In Senegal, average output for the production of groundnuts and cotton, the country's main cash crops, fell by 25% relative to average values for the mid-1960s. In countries such as Chad, Mali, and Niger, the production of cereal crops such as millet and sorghum was similarly affected and fell by about a third in 1973–1974 relative to the mid-1960s (Berg 1976). Overall reduction in agricultural output for some of the worst affected countries such as Chad, Mali, Niger, and Senegal was between 12 and 21%. For people who were already very poor, such impacts reflected an extraordinarily severe loss (Berg 1976).

1.04.3.3.2 Drought Impact in Eastern and Southern Africa

The impact of drought in other parts of sub-Saharan Africa have also been documented including the 1983–1984 Ethiopian famine in which a million people are estimated to have died (Hellmuth et al. 2007) and the 2003 and 2005 droughts in eastern and southern Africa, which threatened the lives of 14 million people (UNECA 2008). On the basis of several studies undertaken at this time, Ramin and McMichael (2009) documented what it meant for a child's nutritional and growth status if born in a drought year. For example, early twenty-first century droughts increased the likelihood of a child being undernourished by 36% in Ethiopia and 50% in Kenya. Such children were also more likely to be stunted relative to their peers (by as much as 2.3 cm) with significant long-term impacts on a range of human well-being indicators including lifetime earnings. The impact of drought was also greatest in poorer households and further exacerbated income inequality particularly within the rural economy, probably because it is usually accompanied by the loss of income and the widespread sale of assets (Benson and Clay 1998).

Ifejika Speranza (2010) carried out a detailed, longitudinal study on the impact of climate variability and drought on 127 agropastoral households located in a semiarid transition zone in southeastern Kenya. In these marginal environments, which receive less than 800 mm per annum, agropastoralism, nomadic pastoralism, and conservation are the major land-use practices. Since 1980, the region has experienced seven major droughts with the 1999–2000 drought resulting in the loss of 52% of the livestock kept by households. Nonclimatic factors, including the failure of livestock and food markets; local conflicts over resources; and an increase in livestock theft also contributed significantly to the impact of drought on people and the environment.

The severe economic impact of the 1991–1992 drought in South Africa provides some measure of the extent to which even relatively complex economies are affected by drought. Pretorius and Smal (1992) suggested that this particular drought resulted in a 27% decline in agricultural GDP, which directly accounted for a 1.5% fall in overall GDP and the further spending of over US$600 million on maize imports in 1992 alone and which continued to 1995. Over the same period, 49 000 agricultural sector jobs and 20 000 formal, nonagricultural sector jobs were lost (Benson and Clay 1998).

1.04.3.3.3 Impact of the 2010–11 Drought Crisis in the GHA

Since the last quarter of 2010, severe drought in the GHA has resulted in widespread famine, loss of human life, loss of livestock, and mass migration. While it is still too early to assess the full impact of this disaster, first reports indicate that the lives of about 12 million people in the region have been affected, a third of whom are from war-torn Somalia (Loewenberg 2011). As many as 3.7 million people are food insecure, with more than 390 000 children considered acutely malnourished. The drought has led to widespread migration, particularly in southern Somalia, and some refugee camps in neighboring countries such as in northern Kenya have received an average of 1300 people a day. Overcrowding and unsanitary conditions have led to widespread outbreaks of life-threatening diseases such as diarrhea and measles. Acute malnutrition affects nearly a third of the refugees in some camps, with conditions on the outskirts of these camps even more dire. High poverty levels and the inability of people to afford the 300% rise in the price of local grains have exacerbated the problem as has conflict and war in the region. Loewenberg's (2011) editorial provides a distressing account of the scale and impact of the tragedy in the GHA, which has experienced its worst drought in 60 years. It also highlights the confounding effect that nonclimatic factors, such as civil conflict and food prices have on the well-being of people living under such conditions.

1.04.4 Land Use and Land Cover Change

1.04.4.1 Agriculture, Ecosystem Productivity, and Soil Erosion

Although estimates vary, about 12% of Africa's land surface is used for agriculture, by far the majority of which is rain fed (Mayaux et al. 2004) (Table 2). While the act of tilling the soil provides food for Africa's growing population, inappropriate cultivation practices can also have devastating consequences for both on- and off-site environments primarily through soil loss, reduction in soil fertility, and ecosystem productivity. Recent satellite-derived estimates of soil erosion in sub-Saharan Africa show that it is most serious in the humid subtropics and tropical savannas, as well as in some of the semiarid areas in the southwest (Symeonakis and Drake 2010) (Figure 6). High rates of erosion are related to slope steepness, soil erodibility, rainfall, and the impact of land use.

1.04.4.1.1 Eastern Africa

Within the northern Highlands of Ethiopia, satellite-derived indices of land degradation suggest that despite the widespread introduction and success of soil water conservation (SWC) measures in the region (Frankl et al. 2011), ecosystem productivity has declined in the past 10 years over large areas (Rowhani et al. 2011). Gebresamuel et al. (2010), for example, describe the negative effects of land-use change between 1964 and 2006 in two catchments from the highlands of Tigray. Both areas showed a substantial increase in settlement area and cultivated land and a decrease in forest and woodland over

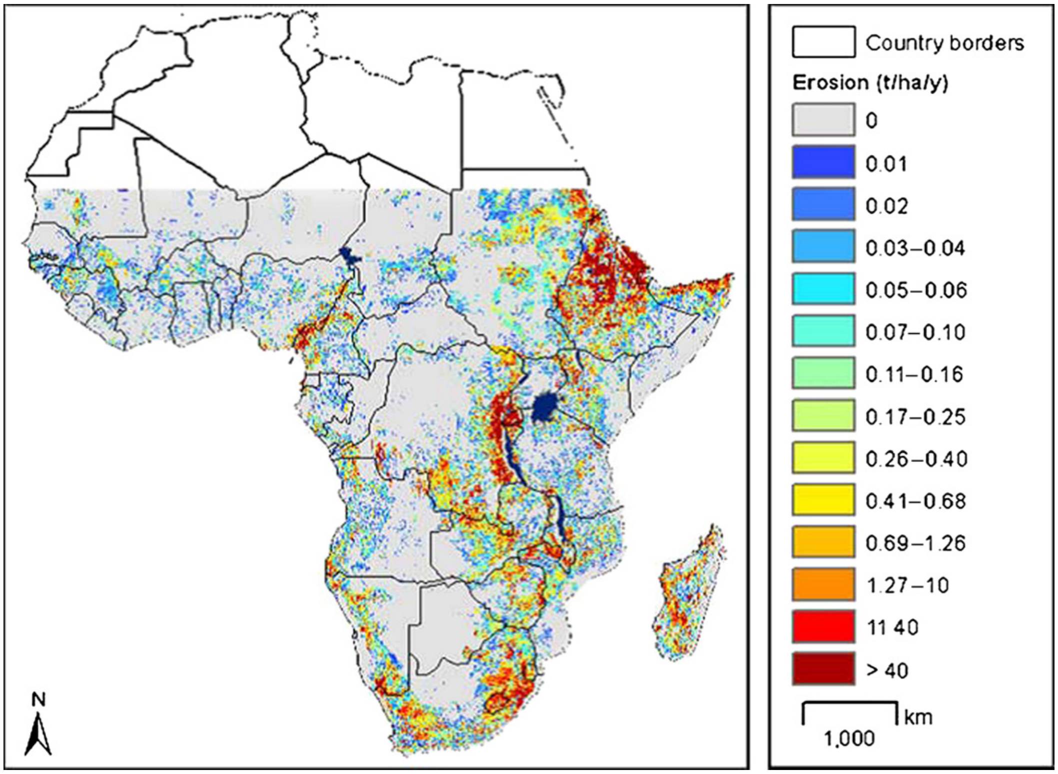

Figure 6 Satellite-derived estimates of the extent of soil erosion (tonnes per hectare per year) in sub-Saharan Africa. From Symeonakis, E., and N. Drake, 2010: 10-Daily soil erosion modelling over sub-Saharan Africa. *Environ. Monit. Assess.*, **161,** 369–387.

time. Surface runoff increased and soil water storage capacity decreased in both catchments in response to the changes in land use and land cover over this period. In southern Ethiopia, Moges and Holden (2008) describe a rapid down-slope development of gullies over the past 30 years, with average soil loss rates of 11–30 $\mathrm{t\,ha^{-1}\,year^{-1}}$, which they suggest are unsustainable in terms of the agricultural production levels required in the future.

Using the 1981–2003 NOAA-AVHRR NDVI time series, Bai and Dent (2006) assessed the extent of environmental change in Kenya. Net primary production (NPP) decreased in 20% of Kenya primarily within marginal cropping environments. In UNEP's Atlas of Kenya's changing environment (2009), the subdivision of marginal land into uneconomic production units, as well as the influx of large numbers of people into increasingly marginal arid and semiarid areas, is blamed for the increase in the extent of degraded land, which is thought to affect nearly 12 million people.

Rohde and Hilhorst's (2001) analysis of 26 repeat photographs from the Lake Manyara area in northern Tanzania provide evidence of dramatic change and, in some instances, severe land degradation associated with cultivation. The most extensive degradation was recorded in the more marginal environments of the Ardai and Makuyuni Plains, which are characterized by low and variable rainfall. Here, extensive cultivation and subsequent abandonment of old lands has resulted in widespread gully erosion and increased runoff from cultivated fields particularly during extreme rainfall events.

1.04.4.1.2 Southern Africa

The 0.9 million $\mathrm{km^2}$ Orange River catchment is the largest in southern Africa and the most turbid in Africa (Compton et al. 2010). Using estimates of mean mud flux derived from marine cores on the western margin of South Africa that span the last 11 500 years, Compton et al. (2010) have suggested that land-use practices associated with settled agriculture in the catchment could have resulted in a sediment discharge as high as 60 million metric tons/year. The mud flux value associated with such a discharge rate is 10 times greater than average values for the Holocene. This, in turn, translates to a 100-fold increase in total soil erosion compared to values for the catchment before settled agriculture.

A national review of land degradation in South Africa (Hoffman and Ashwell 2001) suggested that soil erosion was influenced by both biophysical and socioeconomic factors. Land tenure as well as poverty indices, for example, were both significant predictors of the extent and severity of land degradation in a district as were slope steepness and soil erodibility (Hoffman and Todd 2000). Communally managed areas have consistently returned greater rates of land degradation in Southern Africa (McCann 1999), although there is considerable variability between areas (Wessels et al. 2007). The most important impacts of soil erosion include a decline in crop yield and greater susceptibility to drought; an increase in the rate of dam, reservoir, and estuary siltation (Boardman and Foster 2011); and, in severe cases, the loss of arable land (Garland et al. 1999).

1.04.4.2 Pastoralism and Rangeland Degradation

The livestock production sector is an important activity and source of income for more than 200 million Africans across the continent. It is carried out under a wide range of tenure arrangements and production systems including industrial, agropastoral and pastoral, and smallholder crop-livestock systems (Thornton et al. 2006). Livestock are important assets for any household and help to diversify risk and improve resilience to unexpected shocks such as drought. Livestock also provide a range of spiritual, religious, and economic services for their owners in addition to meat, milk, draught power, and transport. Vulnerability to livestock loss or production failure is influenced by several factors including drought, theft, and land degradation.

Land degradation and the impact of livestock on the composition of African rangelands and their continued ability to provide the necessary services has been the subject of considerable debate over the past two decades (Vetter 2005) and has important implications for how rangelands have been managed (Rohde et al. 2006). While the 'new thinking' in rangeland ecology (Ellis and Swift 1988; Behnke et al. 1993) challenged received wisdom concerning the nature, extent, and causes of land degradation, individual case studies as well as experimental quantification (Du Toit et al. 2009) continue to highlight the impact of persistent high stock numbers on the structure and function of African rangelands. For example, in both the southeastern (Abate et al. 2010) and southwestern (Gil-Romera et al. 2011) parts of Ethiopia, where pastoralism and agropastoralism are the dominant land-use practices, the long-term impact of high human and livestock densities has resulted in significant encroachment by woody plants onto previously productive grassland environments. Most herders themselves consider their rangelands to be in a 'poor condition' (Abate et al. 2010), with important implications for the livelihoods of user communities. For example, ongoing drought conditions together with the extensive degradation of rangeland resources have increased poverty levels in the eastern parts of Ethiopia and have also affected herd composition with camels and small ruminants replacing cattle (Kassahun et al. 2008).

In South Africa, where livestock mobility is severely constrained by overcrowding and the historical legacies of apartheid planning, heavy stocking rates have transformed significant parts of the country. This is particularly visible in the communal areas where stocking rates are on average 1.85 times greater than neighboring private leasehold farms (Hoffman and Ashwell 2001). In the communal areas of semiarid Namaqualand, in the western part of South Africa, heavy grazing has resulted in the reduction of palatable perennial plants and an increase in annual and geophytic species (Anderson and Hoffman 2007). However, the impact appears spatially heterogeneous with lowland environments affected to a far greater degree than rocky upland environments (Anderson and Hoffman 2011). The transformation from a perennial shrubland to an annual, herb-dominated flora renders such transformed ecosystems vulnerable to the impact of drought since, when rains fail, very little forage is available for livestock. In contrast, within perennial shrub-dominated landscapes, the potential at least exists for the interannual transfer of forage production, which buffers the fluctuations in livestock production to some extent (Todd and Hoffman 2009). However, despite the impact that heavy grazing has had on both plant composition and soil fertility in the region, Benjaminsen et al. (2006) have shown that very high livestock numbers can be maintained over decades in the communal areas even though they fluctuate significantly in response to drought and good rainfall conditions.

1.04.4.3 Bush Encroachment

Bush encroachment is the increase in cover, density, and biomass of indigenous woody trees and tall shrubs (van Auken 2009). It has transformed the structure and function of many savanna and grassland environments across Africa, with important consequences for ecosystem services and agricultural-based livelihoods (Kassahun et al. 2008) (Figure 7). While some consider it a cyclical phenomenon (Wiegand et al. 2006; Gil-Romera et al. 2010), others consider it a progressive process and a problem primarily of the twentieth century (Rohde and Hoffman 2012). In some instances, it also reflects a return to the kind of landscape that existed prior to it being cleared for cultivation (Puttick et al. 2011). While estimates of the extent of bush encroachment for the continent are lacking,

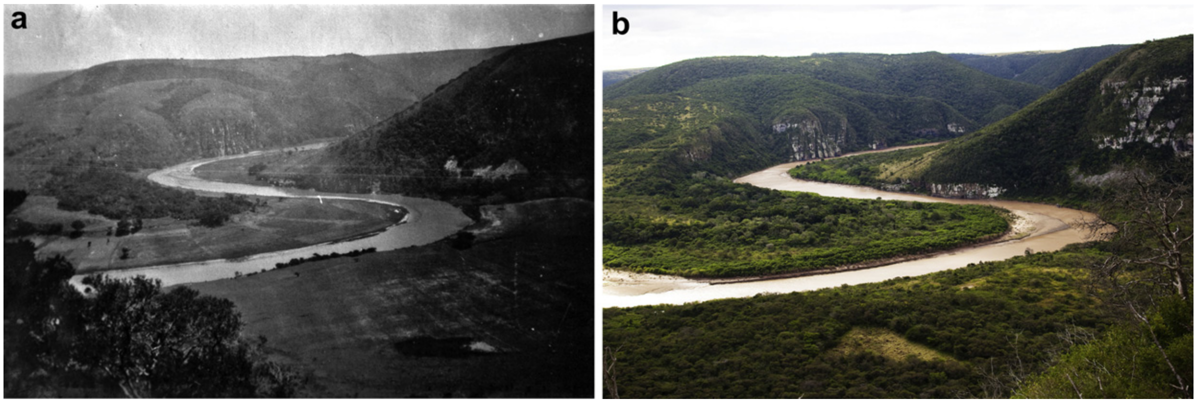

Figure 7 Change in woody plant cover on abandoned cultivated fields and on slopes and ridgelines near the mouth of the Kei River, South Africa between *c.* 1920 (left) and 2011. Unpublished photograph reproduced with permission from James Puttick.

in some countries, such as Namibia, as much as 12 million ha are heavily encroached upon by 'problem bushes' (De Klerk 2004).

Depending on prevailing rainfall conditions and disturbance regimes (Bucini and Hanan 2007), increases in tree cover can be rapid. Munyati et al. (2011), for example, recorded a 50% increase in bush-encroached areas at a mesic South African savanna site in as little as 6 years, while in another mesic South African savanna, woody plant density increased by 194% over three decades (Buitenwerf et al. 2011). Woody plant increase is far less of an issue in arid savannas. For example, in Namibia, areas below a mean annual rainfall of 275 mm have not exhibited an increase in woody plant cover over more than 130 years (Rohde and Hoffman 2012).

Several reasons for the increase in tree cover have been proposed, including both local (e.g., soils, grazing, and fire) and global (e.g., CO_2 enrichment) drivers (Ward 2005). For example, Augustine and McNaughton (2004) have shown experimentally for a savanna in central Kenya that the loss of both small selective browsers (e.g., dik-dik (*Madoqua kirkii*)) and large bulk feeders (e.g., elephants (*Loxodonta africana*)) significantly affected the recruitment and establishment dynamics of key encroaching shrub species. Both light and heavy grazing by domestic livestock together with fire suppression also appear important determinants of the rate and extent of bush encroachment (Munyati et al. 2011). Because bush encroachment occurs in both heavily grazed and lightly grazed regions under fundamentally different tenure regimes (Wigley et al. 2010), there is an emerging view that increased atmospheric CO_2 concentrations play a primary role in the process through its influence on the growth rate and competitive ability of encroaching tree species, particularly in terms of their response to fire and herbivory (Bond and Midgley 2012; Buitenwerf et al. 2011). The process of encroachment is also spatially heterogeneous with low-lying alluvial substrates losing cover and hillslopes gaining cover at some locations (Levick and Rogers 2011). Most studies of the impact of bush encroachment have focused on the effect it has had on ecosystem structure and community composition (Table 3).

1.04.5 Invasive Species

Invasive alien species can be defined as those nonnative species that threaten ecosystems, habitats, or species (Convention on Biodiversity 2008). Through their impact on the environment, alien invasive species contribute indirectly to poverty, food insecurity, ill health, and poor water quality (MA 2005) and affect a range of ecosystem services including provisioning, regulating, and cultural services. Vitousek et al. (1997) provide estimates of the number of alien species in Africa (Table 4).

Water quality and supply are critical for human health and well-being, but water resources and their associated ecosystems are also particularly vulnerable to impact from alien invasives. For example, water hyacinth (*Eichhornia crassipes*), a South American native, is a problem in tropical and subtropical waterways globally. Despite being present in Africa from as early as 1900, it is only over the past 30 years that it has become a severe and widespread problem across the continent. The problems caused by this weed are best illustrated by the impacts of *E. crassipes* on Lake Victoria. In the mid-1990s, the lake was infested by up to 20 000 ha of *E. crassipes*, which floated around the lake in huge mats and infested inlets and fishing beaches along the shoreline (Moorhouse and Albright 2002). The impacts of the infestation were extensive and negatively affected agriculture, hydroelectric power generation, fisheries, lake transport, recreation, and water quality and supply for both domestic and industrial use. Kasulo (2000) estimated the annual cost of the hyacinth in Lake Victoria and the other Great Lakes in terms of its impact on fisheries alone at US$71.4 million. Across Africa, the costs may be as much as US$100 million annually (UNEP 2007). Although biocontrol agents have largely brought the weed under control, it remains present, albeit at lower densities, across most of the waterways that have previously been infested.

Table 3 Some of the main impacts of bush encroachment on ecosystem structure and function as well as on the services that ecosystems provide for human well-being in Africa

Country and/or region of study	*Main effect*	*Source*
All savannas and grasslands	Feedbacks to earth–atmosphere systems and regional climates through changes in albedo and reduction in fire emissions	Bond and Midgley (2012)
All savannas and grasslands	Increase in shrub cover, total soil C and N, decrease in grass cover and soil pH	Eldridge et al. (2011)
Namibia	Increase in runoff and lower infiltration of water to subsoils	De Klerk (2004)
Namibia	Increase in woody biomass and availability of firewood	De Klerk (2004)
Ethiopia; Namibia; Southern Kalahari, South Africa	Change in plant species composition and richness, particularly of the grass and herb layer	Angassa (2002); De Klerk (2004); Wasiolka and Blaum (2011)
Southern Kalahari, South Africa; Southern Ethiopia	Change in vegetation structure with knock-on effects for faunal species composition, density, and richness (including arthropods, reptiles, birds and mammalian carnivores)	Blaum et al. (2007, 2009); Spottiswoode et al. (2009); Sirami et al. (2009); Wasiolka and Blaum (2011);
Namibia, Ethiopia	Reduction in carrying capacity for both communal and commercial area cattle production with significant negative impact on livelihoods and agricultural GDP	Hoffman et al. (1999); De Klerk (2004); Gil-Romera et al. (2010)

Table 4 The number of native and alien flora species within various broad regions and countries of Africa

Region/country	*Area (km^2)*	*Number of native species*	*Number of established alien species*	*Percentage of alien species*	*Number of alien species per log (area)*
Western and central Sahara	4 000 000	830	$<$28	$<$3.3	$<$4.2
Tropical Africa	22 300 000	23 500	536	2.2	72.9
Southern Africa	2 693 389	20 573	824	3.9	128.1
Egypt	1 000 250	2015	86	4.1	14.3
Djibouti	23 000	641	44	6.4	10.1
Uganda	236 040	4848	152	3.1	28.3
Rwanda	26 338	2500	93	3.6	21.1
Namibia	824 293	3159	60	1.9	10.1
Swaziland	17 366	2715	110	3.9	25.9
Cape region	90 000	8270	441	5.1	88.9

Extracted from a larger table provided in Vitousek, P. M., C. M. D' antonio, L. L. Loope, M. Rejmánek, and R. Westbrooks, 1997: Introduced species: a significant component of human-caused global change. N. Z. J. Ecol., 21, 1–16., which also lists the original source of the data.

In some cases, changes to the terrestrial system can also have a large impact on water resources. For example, it is estimated that the reduction in surface water runoff as a result of terrestrial woody plant invasions in South Africa was >3000 million m^3, or around 7% of the total value for the country (van Wilgen et al. 2008). Reduction would increase to an average of 46% across five major biomes in South Africa if the potential range of invasive alien plants were to be occupied (**Table 5**). Additional impacts associated with the invasion of woody species include changes to livestock production, biodiversity, fire intensities, increased soil erosion, reduced tourism, and a decline in recreation value. Costs of invasions amount to nearly US$1 billion annually or 0.3% of South Africa's GDP (van Wilgen and De Lange 2011). This could increase to 5% if alien plants were to occupy their full potential range. In a study involving just one of the most serious woody invasives, the black wattle, *Acacia mearnsii*, De Wit et al. (2001) demonstrated that a 'net present cost' of US$ 1.4 billion could be attributed to black wattle invasions in South Africa.

The economic evaluation and quantification of these impacts has been a critical action that has provided support for policies and leveraged funding for proactive management of alien plants in the country. The Working for Water Program is a state-funded response to these studies and aims to increase water supply and associated ecosystem services by clearing alien woody plants from catchments and riparian areas. It has been possible to justify the spending of over US$ 500 million on the program between 1995 and 2004 (Van Wilgen et al. 2008). A novel aspect of the program is that it also runs a parallel social development program that seeks to maximize the opportunities for development of disadvantaged people employed by the program.

Table 5 Potential future impacts of invasive alien plants on key ecosystem services in five biomes of south Africa

	Reduction relative to biome values without alien plants (%)		
Biome	*Mean annual surface water runoff*	*Number of livestock units*	*Biodiversity intactness*
Fynbos	37	67	58
Grassland	50	74	55
Succulent Karoo	60	38	85
Nama Karoo	29	72	96
Savanna and thicket	54	72	61
Average	46	65	71

Compiled from data in Van Wilgen B. W., B. Reyers, D. C. Le Maitre, D. Richardson, and L. Schonegevel, 2008: A biome-scale assessment of the impact of invasive alien plants on ecosystem services in South Africa. *J. Environ. Manag.* **89,** 336–349.

Pimentel et al. (2001) provide an insightful review of the economic costs of the alien invasive species and show that the relative costs are higher in developing compared to developed nations. Using agricultural GDP in 1999 as the benchmark, Perrings (2011) demonstrates using the Pimentel estimates that invasive species caused damage costs equal to 53% of the agricultural GDP in the United States, 31% in the United Kingdom, and 48% in Australia. In contrast, damage costs in South Africa, India, and Brazil were, respectively, 96, 78, and 112% of the agricultural GDP. Since alien species are not more prominent in the latter countries as compared to the former developed nations, this indicates that alien species impact the economy and especially the rural communities of developing nations disproportionately more than those of developed nations. The authors do not attempt to explain this disparity, but it may be related to the less intensive nature of agriculture in the less developed nations and a reduced capacity to directly tackle the invasive problems.

1.04.6 Historical Trajectories and Counter Narratives

1.04.6.1 Temperature and Evaporative Demand

Temperature data for Africa confirm a warming trend of about 0.5 °C for the twentieth century, which is similar to that experienced globally over the same period (Hulme et al. 2001), although there is evidence that this increase in the mean is from increases in the minimum, night time temperature possibly due to land surface change and low level atmospheric aerosols (Christy et al. 2009). Using the Palmer Drought Severity Index as a measure of drought, Dai (2011b) reported a widespread drying trend for Africa over the period 1950–2008, which is consistent with observed decreases in streamflow. This trend is ascribed primarily to the impact of recent warming, especially since the mid-1980s, and not to changes in precipitation. In contrast, studies of direct evaporative demand (as opposed to modeled values) in southern Africa have shown a decrease in pan evaporation (E_{pan}) in the latter part of the twentieth century (Eamus and Palmer 2007; Hoffman et al. 2011). Despite a significant increase in temperature between 1974 and 2005, E_{pan} values in the winter rainfall region of the Western Cape of South Africa declined by an average of 9.1 mm per year, at 16 of the 20 stations investigated, primarily in response to a 25% decline in wind run over the same period. This twentieth century decline in evaporative demand in response to wind stilling has been documented globally (McVicar et al. 2012) and has yet to be satisfactorily explained in terms of prevailing climate science theory (Roderick et al. 2009). It remains a critical issue for African climate research particularly since a decrease in evaporative demand, even with an increase in temperature, would increase plant water use efficiency, NPP, and biomass accumulation (Eamus and Palmer 2007).

1.04.6.2 Precipitation and Vegetation Change

1.04.6.2.1 The Sahel

In the Sahel, for most of the past two decades, annual rainfall totals have been similar to those of the first half of the twentieth century, with a concomitant response in the vegetation (Herrmann et al 2005; Huber et al. 2011). This climate–vegetation response has been tracked primarily by using the NDVI calculated at a spatial resolution of 8 km from the NOAA series of AVHRR satellite imagery (Tucker et al. 2005; Bégué et al. 2011). Excluding the most recent drought in the Sahel and the GHA (Gebrehiwot et al. 2011), the general pattern that emerges for the region and indeed, for most of the world's drylands (Hellden and Tottrup 2008), is that of an overall increase, since the early 1990s, in photosynthetically active vegetation, and by inference NPP (Olsson et al. 2005; Prince et al. 2007). Much of this increase can be explained by either the increase in rainfall (Anyamba and Tucker 2005; Hickler et al. 2005; Hein et al. 2011) or soil moisture (Herrmann et al. 2005; Huber et al. 2011) that has been experienced in the region over this period. While there are some differences across the more than 3 million km^2 that comprise the Sahelian zone (Huber and Fensholt 2011), the general trend of increasing vegetation greenness since 1982 has high spatiotemporal consistency across the region (Hellden and Tottrup 2008) (Figure 8).

1.04.6.2.2 Eastern Africa

As in the Sahel, rainfall in East Africa is significantly influenced by SST over the equatorial regions of the Pacific, Indian, and the southern Atlantic Oceans and the movement of moisture by large-scale atmospheric circulation patterns (Segele et al. 2009). Drought conditions appear to be associated with El

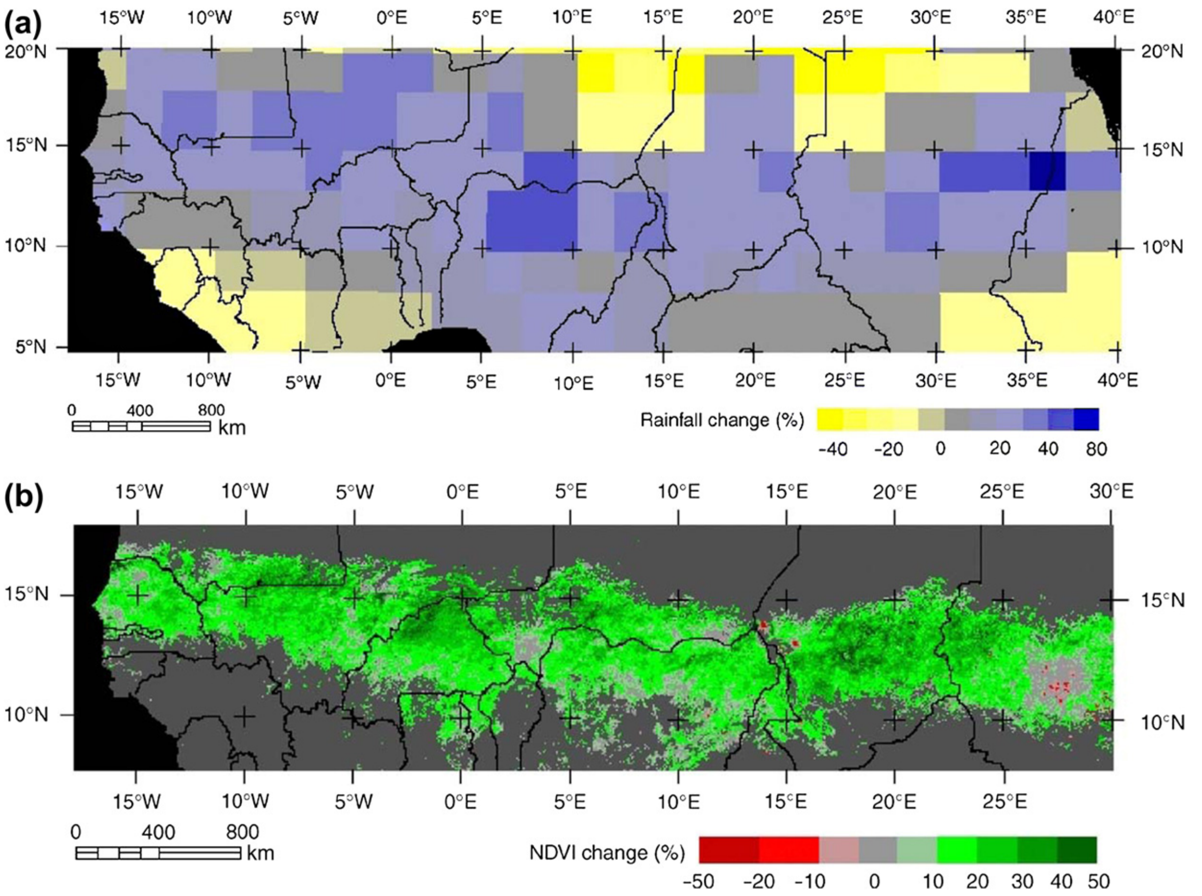

Figure 8 The general increase in monthly rainfall over the period 1982–2003 (a) is primarily responsible for the increase in vegetation greenness (b) observed across the Sahel using NOAA-AVHRR NDVI values. From Herrmann, S. M., A. Anyamba, and C.J. Tucker, 2005: Recent trends in vegetation dynamics in the African Sahel and their relationship to climate. *Global Environ. Change* **15,** 394–404.

Niño conditions and wetter periods with La Niña conditions in the Pacific (Segele et al. 2009). While Ethiopia experienced significant drought in the 1970s and the 1980s (Araya and Stroosnijder 2011), long-term trends in mean annual rainfall do not show a significant decline in the central, northern, and northeastern parts of the country over the latter part of the twentieth century (Seleshi and Camberlin 2006; Cheung et al. 2008). However, drought conditions have prevailed in the southern and eastern regions over the last decade (Gebrehiwot et al. 2011; Rosell 2011).

What has been the response in the vegetation of the region? Repeat photograph studies provide an important counter to the generally catastrophic degradation narrative that has been proposed for Ethiopia (Amacher et al. 2004; Gebresamuel et al. 2010), which suggests that forest cover in Ethiopia has declined from 40% of the land surface in 1885 to as little as 4% by 1985 (McCann 1999). For example, a comparison of 13 photographs from northern Ethiopia, which were first taken in 1868 and then 140 years later in 2008 by Nyssen et al. (2009), show a significant improvement in key ecosystem health indicators such as vegetation cover and soil retention despite a 10-fold increase in the number of people (Figure 9). As in the Machos district in Kenya (Tiffen et al. 1994), the generally positive changes are ascribed to the intensification of land-use practices as well as the widespread implementation of soil and water conservation measures that have occurred in the region since the 1970s.

Similar studies, using repeat photography, have been carried out in other parts of northern Ethiopia but over shorter time periods. For example, Munro et al. (2008) examined 51 matched photographs to document the impact of changing land-use practices in Tigray over the period 1975–2006. Like Hagos et al. (1999) they emphasized the causative links between drought, poverty, war, and land use and how this combination of factors led to widespread degradation in the region particularly during the last few decades of the twentieth century. Their findings suggest that the large-scale SWC measures, started in the 1970s, and that included the building of stone bunds and exclosures, have resulted in a general increase in vegetation cover and a concomitant reduction in soil loss of more than 30% when compared to 1975 levels. Besides the control of soil erosion (Mekuria et al. 2009) and a significant increase in soil organic matter, nitrogen, and phosphorus (Mekuria et al. 2007), additional benefits include improved water flow and a more efficient use of water for biomass production (Descheemaeker et al. 2009). Other repeat photograph studies of landscape change (Nyssen et al. 2008; Frankl et al. 2011) reach similar conclusions and confirm that degradation is reversible, although not without significant effort and sacrifice, particularly on the part of local farmers (Hagos et al. 1999). Success appears greatest where SWC measures provide tangible benefits for rural livelihoods such as an increase in crop yields and where there is also a high demand for agricultural land (Boyd and Slaymaker 2000).

1.04.6.2.3 Southern Africa

The western part of southern Africa, especially the Succulent Karoo biome and southern Namibia, is projected to be most affected by future warming (Tadross et al. 2011). However, analyses of historical climate trends suggest that there has been no significant increase in the incidence of drought in the Succulent Karoo biome since 1951 (Hoffman et al. 2009) and neither do rainfall patterns for the twentieth century appear significantly different than those for the nineteenth century (Kelso and Vogel 2007). While there are differences in long-term precipitation trends between individual climate station records in the Namaqualand region of the Succulent Karoo biome (MacKellar et al. 2007), the vegetation of the ephemeral rives, plains, and slopes appears to have increased in cover over the course of the twentieth century (Hoffman and Rohde 2007,

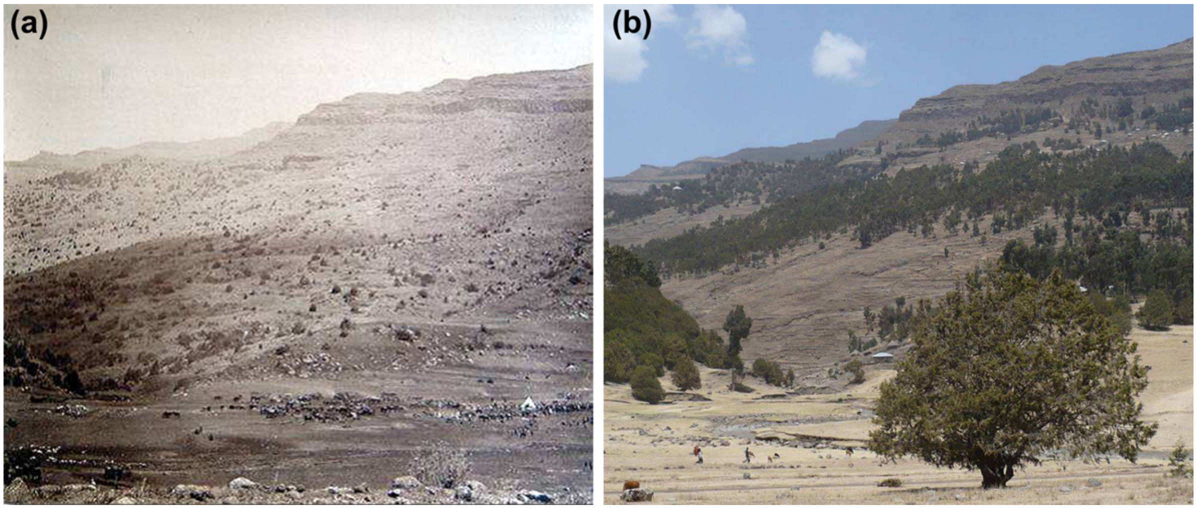

Figure 9 This repeat photograph pair taken in the mountainous Tigray Region of Ethiopia illustrates some of the complex changes in land-use practices and vegetation that have occurred since 1868 (a) when the original photograph was taken and 2008 (b). Settlement density has increased considerably as has the area that has been cropped. Forest cover has increased on the distant hillslopes, which were more sparsely vegetated and more eroded in 1868. However, the erosion gully running through the foreground slopes was not present in 1868. From Nyssen J., and Coauthors, 2009: Desertification? Northern Ethiopia re-photographed after 140 years. *Sci. Total Environ.*, **407,** 2749–2755, Supplementary data.

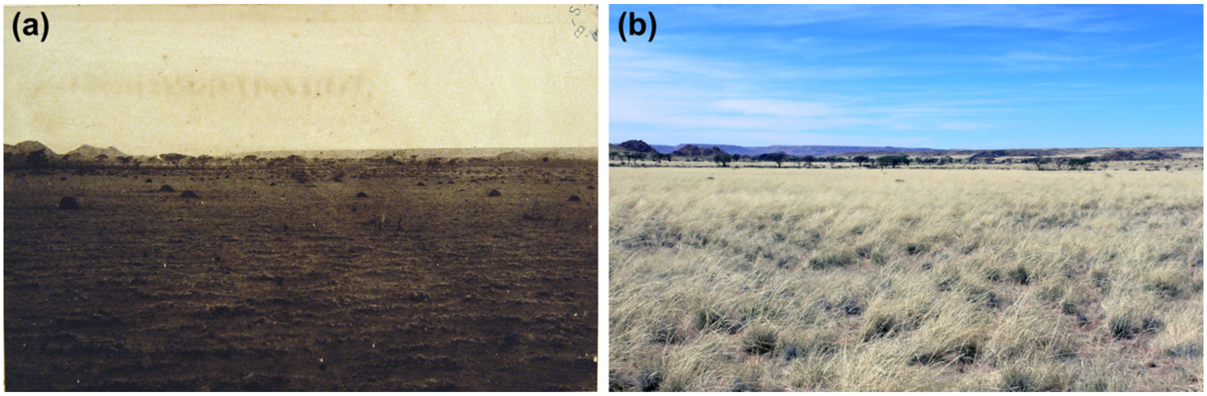

Figure 10 Vegetation change at Kunjas Farm in southern Namibia near Helmiringhausen between 1876 (a) and 2008 (b). While there has been an increase in the ephemeral grass component, the long-lived *Acacia erioloba* trees have remained stable over time. Unpublished photograph reproduced with permission from south African Libraries and Rohde and Hoffman.

2011) even under the heavy grazing regime within the region's communal areas (Rohde and Hoffman 2008). The primary reason for this is the abandonment of agriculture in marginal environments, the switch to commercial sheep breeds, and the associated reduction in stock numbers in the latter part of the twentieth century (Hoffman and Rohde 2007). Spatial patterns and temporal trends in NDVI for the period 1981–2003 confirm that there has been an increase in climate-adjusted NPP in the western part of southern Africa (Bai and Dent 2007).

The arid and semiarid regions of southern Namibia have also been remarkably stable over more than a century, and little sign of aridification, as projected for the next 40 years (Midgley et al. 2005), is evident in any of the nearly 50 repeat photographs taken for the region, which span more than 130 years of environmental history (Rohde and Hoffman 2012). While ephemeral grasses have fluctuated in response to seasonal changes in rainfall there is no evidence of widespread degradation associated with arid shrubland expansion at the expense of grassy savanna vegetation (Figure 10).

1.04.7 Future Research Challenges

Environmental change in Africa is influenced by a complex suite of direct and indirect drivers operating and interacting at different spatial and temporal scales (Dawson et al. 2010). Their impact on ecosystem processes and states has important consequences for the services provided by the environment and for human well-being. This review has highlighted the nature, extent, and impact of environmental change on the continent and has emphasized the considerable uncertainty that exists in future projections. Such uncertainty will be compounded by the rapidity of social change, including urbanization and land tenure reform (UNECA 2004). To better adapt to this change we need to address the following key issues.

- Improve our understanding of the extent and pattern of past environment change in Africa over both short (years to decades) and long (centuries to millennia) temporal scales and how it has affected the supply of critical ecosystem services and human well-being over time;
- Develop a more comprehensive analysis of how direct and indirect drivers of environmental change interact to influence ecosystem services;
- Evaluate more comprehensively the costs and benefits to society of environmental change both in the present and future and explore the trade-offs that are needed between ecosystem services (e.g., between carbon sequestration, water provision, and biodiversity (Van Wilgen et al. 2008)). To this end, greater investment in scenario planning will be necessary, but these need to document the entire spectrum of what is possible;
- Assess the predictability and, if possible, improve our ability to skillfully forecast future changes in the environment and their implications for different communities, economies, and societies living in different parts of the continent;
- Build a stronger interdisciplinary network within Africa in collaboration with international colleagues and with strong political and institutional support so that problems and solutions can be more easily shared between regions.

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1.05 Ecosystems, Biodiversity, Climate, and Health

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Glossary

Anthropocene A recent period of Earth's history, during which the combined influence of one species – *Homo sapiens* – has acted with sufficient power and scale to change the Earth system.

Biodiversity Abundance of biological variety.

Biophilia Psychological connectivity, including affection and love, felt and expressed by some humans toward other forms of life.

Climate change Alterations of regional and local climate, even statistically.

Ecocentrism A philosophical and attitudinal perspective that gives high value to biological and natural processes; at its extreme, this could lead to the detriment of the well-being of some human beings.

EcoHealth A term that indicates links between human and ecological well-being.

Ecosystems Basic units of nature within which living organisms continually interact with nonlife forms, whose boundaries are arbitrary, and that exist in dynamic equilibrium.

Ecosystem services The benefits provided to humans and other species by nature; examples range from obvious (oxygen, food, water) to subtle (regulation of the carbon cycle) and psychological, including aesthetic beauty.

Green space Parks, playing fields, trees, watercourses, woods, and gardens – areas that are not predominantly paved or used for buildings; generally applied to otherwise urbanized environments.

Human well-being A state of existence in which the basic material needs of people are met and they have freedom and choice, good social relations, personal security, and reasonable health.

Sustainability A process of living within the limits of available physical, natural, and social resources in ways that allow the living systems in which humans are embedded to thrive in perpetuity.

1.05.1 Introduction: Our Growing Disconnection from Nature

More than three million years ago, tool-using hominids (*Australopithecus afarensis*) in modern-day Ethiopia were cooperatively shaping and transporting specialized cutting stones at least 6 km from their source (McPherron et al. 2010). Palaeontologists are confident about this because of knife marks found on several fossilized ungulate bones in an area devoid of suitable material for making stones able to cut such bones. At that time of prehuman development, it is obvious that everything essential to life for these hominids came from the environment – sunlight, stones for tools, animals to hunt, water to drink, air to breath, plants to eat, and probably trees to shelter in. However, it is unlikely that these hominids, who walked upright, could conceptualize this intimate dependence on nature, as cognition is considered, at least in primates, to have coevolved with language, learning, and sociality. Although we can deduce that *A. afarensis* could communicate sufficiently well to hunt cooperatively, it is believed that their capacity for speech as we know it of any kind, let alone discussion, was limited by the presence of air sacs in their larynxes. (These are anatomical structures still found in most of the great apes that disappeared from *Homo* ancestors at least 600 000 years ago. Great apes communicate using a combination of vocalizations, expressions, and gestures, but their capacity to communicate possible complex thoughts is considered to be limited.)

The time by which hominids developed the capacity for complex speech and cognition is uncertain and disputed, but it is certainly ancient. At some stage in this evolution, modern humans or their ancestors must have developed concepts about the environment, its value as a resource provider, and their place within it. This can be deduced by the importance given to land and other environmental elements, such as totem species by indigenous populations, both ancient (Berkes et al. 1998) and modern (Nettleton et al. 2007). Such perspectives include an integrated understanding of the relationships between land and human health.

In 2010, Jacinto Zarabata visited the United Kingdom. He was a spokesperson for the spiritual leaders of the Kogi people, who live in Colombia. The Kogi are making a movie about their way of life in an attempt to warn people in the West ('little brother') to cease destruction of the planet before it is too late. When interviewed about his impressions of London he said:

> "The first thing that is noticeable to me is that this is still the world," he says. "What's visible is construction, what you have made. This is not something we, the Kogi, are used to seeing. You give precedence to the use of a thing rather than its source. That's the intellectual error. Ultimately, it's all nature" (Barkham, 2010).

Earlier, the U.S. ecologist Aldo Leopold wrote (using land as a synonym for ecosystems) in his 1949 classic, *A Sand Country Almanac with Essays on Conservation from Round River* (Foreword, p. viii):

> We abuse land because we regard it as a commodity belonging to us. When we see land as a community to which we belong, we may begin to use it with love and respect. There is no other way for land to survive the impact of mechanized man, nor for us to reap from it the aesthetic harvest it is capable, under science, of contributing to culture.

In this, the second decade of the twenty-first century, more than half of humanity live in urban environments, including hundreds of millions in slums, suburbs, and high-rise apartments. A recent United Nations Children's Fund (UNICEF) report states that one in three urban dwellers lives in slums. In Africa the proportion is almost double (UNICEF 2012). Slums are areas of dense, poor-quality housing, often with limited green space and few trees. The dominant nonhuman mammal may be a rodent carrying diseases such as plague or leptospirosis that can infect humans. In such places, the most common insect encountered may be a mosquito, breeding in puddles and water containers. Such limited and hazardous forms of exposure to nature are unlikely to benefit psychological health. There is increasing recognition of the multidimensional vulnerability of populations who live in slums to climate and climate change, including to floods and food disruption (see 1.26 Case Studies: Addressing Vulnerabilities and Reducing Risks – Vulnerable Countries).

More humans are thus less exposed to rural surroundings and 'wilderness,' that is, uninhabited areas that appear little altered by human action. In many countries, too, rural landscapes have been massively transformed. An example is monocultures, such as corn fields, rice paddies, and palm oil plantations. Yet humans remain part of the natural world, completely dependent on both renewable and nonrenewable natural resources for survival. Even dwellers of high-rise apartments need food, water, and air. Such buildings are made from earthly materials, whether stone, concrete, steel, bamboo, or wood. Plastics, made from petroleum, are fossilized biota.

A psychological distancing from nature has accompanied this physical separation. Until about 1850, in many European cultures, it was accepted and even prestigious (for those able to afford it) to carve animals at the table. Draft animals, such as horses and donkeys, were common in towns, and the countryside was never far away. Indeed, if not living on the land, many had relatives who were farmers and were therefore exposed to rural living. Until comparatively recently, it was also not unusual for humans to be directly involved with the raising and slaughtering of such animals, as is still the case in most parts of the world. However, this daily reminder of our dependency on nature has slowly waned, especially among the most wealthy and influential global class. This class, which disproportionately influences policy (Butler 2000), is arguably the group most distanced from the earlier mentioned sense of dependency on ecosystem services. Although many in this highly urbanized group enjoy the relatively privileged experience of psychological benefits arising through frequent contact with green spaces, such as by living in leafy suburbs, too many of 'the 1%' experience a psychological disconnect with the poor. Surveys suggest that an increasing number of children do not realize that some of their food is grown in the ground. Petting zoos of farm animals are now very popular.

1.05.2 Psychological Benefits of Exposure to Nature

These observations may seem obvious to readers who feel strongly connected with nature, who experience and express what the sociologist and psychoanalyst Erich Fromm called biophilia (love of life), a concept further developed by the biologist E. O. Wilson. Richard Louv has coined the term *nature deficit disorder* to describe how people with limited contact with nature experience increased rates of symptoms, including behavioral disorders, anxiety, and sadness (Louv 2008). Louv, a journalist, is far from alone in this emerging field of psychological health.

The desert cultures of North Africa and Arabia depend on oases not only for water, food, and shade but also for something harder to quantify: a respite from the monotony of sand. Images of paradise always include gardens. The Garden of Eden is a foundational myth for the three Abrahamic faiths, followed by at least half of modern humanity. Hindus and Buddhists have similar visions of verdant, vibrant, and desirable places of natural abundance and interspecies harmony. This multicultural evidence of yearning for nature seems to reflect a deep-rooted recognition of its therapeutic, nurturing value. Qualities that exceed the physical nurturing of food and shelter seem to reach into the human spirit. From quite a young age, all humans know that they will die. Contact with nature (or for some, perhaps stargazing) seems to provide solace, a reminder that we are part of a much larger system that will endure, even if we cannot.

Recognition of the intrinsic value of healthy ecosystems may occur even without the intellectual understanding of the mechanisms involved, as though this valuing transcends the cognitive and lives in the amygdala, the limbic system. Neuroscience has identified these areas of the brain as the seat of fear and anxiety. These primal brain functions emerged very early in animal evolution and provide an important protective mechanism. Strategies within the suite of complementary medical therapies attempt to target the limbic system. They seek to quell feelings of fear and anxiety and to promote a sense of positive well-being by triggering deep limbic senses via music and aroma therapies. Neuroscientific research may, in future, determine that the sense of well-being and comfort humans attribute to the connection with nature is linked to the emotional neuropathways of the limbic system. It is also noteworthy that humans seem most attracted toward healthy ecosystems (Rosnäs et al. 2011), including oceans, and, conversely, feel repugnance and disgust when exposed to rotting, decaying, and contaminated ecosystems that appear unhealthy or unsafe. Hence, it is biologically plausible that such a strong self-protective mechanism evolved to become entrenched in our primitive brain, and it is difficult to access or explain by intellect.

Many humans form strong emotional bonds with pets, and some also feel affinity and attachment to wildlife. This regard is not necessarily limited to animals with which they occasionally interact, but also extend to animals, species, and even entire ecosystems that they never visit. This is evidenced by the growing international phenomenon of support for organizations that try to protect wildlife and biodiversity and also by the popularity of documentaries about nature. It is also evident in terms such as *ahimsa* (reverence for life in Sanskrit) and in the Chipko movement in India, which sought to protect forests in parts of India. In Thailand, some Buddhist monks ordained trees in an effort to protect their diminishing forests. The growing global Green political movement is also strongly motivated by a consciousness of an endangered natural world. Several relevant international professional networks work in the area of ecology and health, such as the International Association for Ecology and Health, the International Society of Doctors for the Environment, and the Global Ecological Integrity Group.

In the 1950s, leading microbiologist and later planetary ecologist René Dubos commented on the reduced human contact with nature that he foresaw evolving, especially in urban areas. Dubos speculated that this would trigger a demand for artificial forms of stimulation, including stimulation through an increased use of drugs. It is possible that Dubos may also have anticipated a growth in electronic stimulation as partial compensation for the loss of contact with nature: the early forms of electronic games and virtual reality were evolving when Dubos was still alive.

The three-dimensional film *Avatar* (2009), which depicts a highly creative universe of synthetic ecosystems and endangered indigenous populations, was a worldwide hit, including briefly in China until it was banned. In the late 1990s, millions of people, mainly in East Asia, formed strong emotional bonds with an electronic toy called the Tamagotchi, which was programmed to need regular tending, including feeding, to prevent it from 'dying' (Levy 2007). Both cases seem to illustrate a yearning for a greater sense of connectedness with other forms of life, be it an animal, a plant, or a human, in a part of the world where children have become uncommon and siblings rare.

Although with a small sample and uncontrolled for socioeconomic status, an early study found that surgical patients recovered faster if they could see out through a window at a natural scene than similar patients in the same hospital with less salubrious views. More rigorous scientific literature in this growing field supports the intuition that exposure to nature brings mental health benefits (Maller et al. 2006). Although earlier studies appear to have commented little on social class, a recent Dutch study found that green space is positively correlated with self-perceived health and mortality and not confounded by social class (Maas et al. 2009).

A confounding explanation for why time passed in nature can be therapeutic is that, during such times, people are distanced from their daily stresses and strains. Many people spend rejuvenating time at the beach, in the countryside, or just walking in the mountains for at least a part of their holiday. It could be argued that recreation are the sole cause of such renewal, irrespective of location. However, if this were the only explanation, then why would so many people be drawn to nature? The desire for solitude is an unconvincing single explanation. Henry Thoreau, whose book *Walden* was extremely popular in the United States in the nineteenth and twentieth centuries, appreciated seclusion. However, Thoreau is remembered principally for his vivid appreciation of nature (Cafaro 2001).

An additional confounding explanation is exercise, which often accompanies exposure to nature. Exercise (especially for people who are primarily sedentary) is mood elevating, even if it is done in a gym or a swimming pool. People from urban backgrounds, who spend more time with nature, are also likely to come from a higher ranked socioeconomic group and therefore may be systematically different from the general population. However, proponents of the mental health benefits of nature argue that the benefits exceed that which is plausible because of these other factors. These benefits include reduced stress reduction, faster recovery from mental fatigue, and a freshened outlook on life. Less certainty exists that benefits for behavioral disorders outweigh socioeconomic disadvantage (Maller et al. 2006).

There is growing recognition that mental disorders, especially depression and anxiety, cause an immense burden of disease (see 1.18, Mental Health and Stress-Related Disorders). It is plausible, therefore, that more contact with nature, especially for urban dwellers, will greatly benefit global health (Rosnäs et al. 2011). Much remains poorly understood. For example, it is plausible that people will benefit more from exposure to a more biodiverse green space than to a green monoculture. Support for this hypothesis exists from studies undertaken in Sheffield, England, a city of about 500 000 people. Investigators reported a positive correlation between psychological well-being and higher levels of biodiversity (plants, birds, and butterflies) among the 312 people they interviewed, when they were exposed to the city's various gardens (Fuller et al. 2007). The socioeconomic status of their informants was not reported.

It is plausible that the more biodiverse parks are in more affluent areas and that interviewees experiencing such parks are better off financially. However, it could be true that people from more disadvantaged areas would gain as great a benefit, or even greater benefit, were they to be more exposed to this biodiversity. Other workers have recently proposed an alternative mechanism, linking psychological well-being with biodiversity and other indicators of ecosystem 'health,' such as ecosystem resilience, organization, and vigor (Dean et al. 2011). Where exposure to nature is limited, humans also gain pleasure and other psychological benefits from contact with fish tanks and from representations of nature, such as photographs, paintings, and computer screensavers. The eminent environmental historian of China, Mark Elvin, stated that in some cases individual trees are venerated as symbolic representations of entire ecosystems.

1.05.3 Sacred Groves and Risks to the Sacred

Humans thus desire, and perhaps at a cellular level *require*, far more from ecosystems than food and water. Most visitors to the diplomatic area of New Delhi are struck by the leafiness of the suburb. In the center of this immensely crowded though extensively forested city, some of the most exclusive hotels maintain small but exquisite gardens. Wealthy people appreciate and can easily afford contact with nature. The urban poor might crave such contact, too, especially if associated with leisure. They survive, in a fashion, without it, but few thrive for it.

Many individuals and groups worldwide, even those who consider themselves 'nonindigenous,' have long recognized the value of certain charismatic and sacred species and groves. The bald eagle is the national bird of the United States. Numerous families, guilds, cities, and nations symbolically honor animals and birds in their flags, logos, and coats of armor. Many cultural symbols, decorations, and ceremonies rely on nature, from sacred plants, fungi, and animals to such seasonal displays as animal migration.

This modern era phenomenon of urban disconnection from nature is significant because the fraction of humanity most separated from nature also has the greatest economic and political influence over the human future. For such a population, perhaps about one billion of the seven billion people alive in this twenty-first century, food commonly is purchased wrapped in plastic or otherwise disguised from its plant, animal, or fungal source. Processed food is increasingly blended with synthetic ingredients, such as preservatives, colors, and flavors. Even cooking is a fading art for some groups.

Food, even if grown hydroponically (i.e., with no soil), was once alive. In March 2012, researchers at Maastricht University reported growing small pieces of muscle about 2 cm long, 1 cm wide, and 1 mm thick in a petri dish. Team leader Professor Mark Post suggests that, in 10 years' time, the commercial production of synthetic meat could reduce the environmental footprint of meat by up to 60% (Ghosh 2012). Currently, all the animal products that humans ingest, consume, or rely on (such as leather and draft animals) are sourced from species that, like us, have the capacity for movement, feeling, and emotion (de Waal 2009), if not complex thought. These animals also require food, water, shelter, and energy. Even if artificial meat could be commercially synthesized and it could deliver the equivalent in micronutrients, it would still require inputs such as energy and raw materials from nature.

The apparent separation from nature by decision makers has another dimension. Many policy makers and corporate leaders behave as if they do not think that civilization is ultimately dependent on natural resources. As discussed, although some of them also appear to express limited biophilia (Ted Turner, founder of CNN, is a noted exception; among his efforts is the preservation of large sustaining herds of bison), many of the most privileged and powerful do experience firsthand exposure to nature. Some people seem to experience an additional form of separation, such as young Wall Street traders. This separation can be expressed perhaps as insufficient identification not only with nature, but also with other people, especially the poor and disempowered. But there is a third element here. Politicians and decision makers in all but the worst autocracies do heed public opinion. It follows, therefore, that not enough people, whether in wealthy economies or countries such as Europe, Japan, the United States, or Australia or in poorer countries including China and India, fully appreciate the collective danger that humanity faces this century and perhaps in the next as we pass through a narrowing funnel of risk.

Surveys consistently report sentiments at least moderately sympathetic to the environment across differing nations and demographic groups (Dunlap et al. 2000). Nevertheless, contrary to these findings, a comparatively *low* commitment to ecological and environmental protection can be deduced by our collective behavior and national policies. This value system has been dubbed the dominant social paradigm, distinct from an environmental paradigm (Dunlap et al. 2000).

From an ecosystemic perspective, there is a relentless global drive toward increased provisioning of ecosystem services, especially to feed the world's population. This occurs at a cost to biodiversity and other vital ecosystem components and services, such as carbon regulation and landscape 'health.' Reflecting this dominant social paradigm, existing geopolitical systems that value the accrual and control of money-generating sources above all else are destined to undervalue natural resources – to their detriment.

Unfortunately, this manifestation is often combined with the neoliberal view that natural bounty is limitless because it is perpetually and perfectly regenerative; therefore, exploitation can persist at higher and higher intensities without ever depleting nature's capital. The more skeptical view is that underlying such ravages of exploitation is the motive pervasive in the Tragedy of the Commons (Hardin 1968), which may be expressed simply as follows: 'because common goods are there for the taking, I must maximize my personal gain before the chance is lost to others.'

This transformation is driven at a deep level by two mechanisms: the enormous expansion of human populations since the last century and, even more fundamentally, humanity's conceit engendered by its industrial ingenuity and seeming mastery of energy, an illusion perpetuated by the temporary abundance of oil and other fossil fuels (see 3.4, Vulnerabilities of Energy Resources and Resource Availability – Fossil Fuels (Oil, Coal, Natural Gas, Oil Shale)). There are now numerous warnings that these processes are unsustainable, thus placing not only human health and well-being, but also planetary ecosystems and civilization itself at increasing risk (Butler and Weinstein 2011). This risk is likely to manifest through multiple pathways, including the emission and accumulation of greenhouse gases, aerosols from industrial and vehicular emissions, and biomass burning, and from land use change including deforestation (National Resource Council [NRC] 2005). Diverse, adverse human feedbacks to emerging scarcities, including large-scale conflict, appear all too plausible (McMichael 2012). Indeed, such consequences have been conceptualized as 'tertiary' effects, in contrast to more direct effects that are smaller in scale (Butler and Harley 2010). The 2003 heat wave in Europe – at least partially, a primary effect of climate change – killed as many as 70 000, mostly elderly, people (see 1.15, HeatRelated Morbidity and Mortality). Flooding in Pakistan in 2010 – another primary effect – temporarily displaced 20 million people (see 1.17, Climate, Precipitation, and Flood Hazards). Large as these events were, their scale may be dwarfed by tertiary effects, such as the permanent displacement of tens of millions of people from the coastline around the Bay of Bengal and other low-lying regions. This seems inevitable if greenhouse gas emissions continue on their current trajectory (see 1.5, Sea-Level Rise and Coastal Inundation).

Although the proportion of humans involved in war has declined (Pinker 2011), this has coincided with improved living standards largely underwritten by cheap fossil fuel energy. As these supplies become depleted, the price of food and other necessities will rise further, driving competition and discontent. Unless these trends can be urgently reversed, it seems very likely that humans will again turn to large-scale violence, as was the case in famine-affected parts of northeastern Africa in 2011. Violence is of course not restricted to low-income countries; it is now widely accepted that resource scarcity (oil) was a fundamental reason for the invasion of Iraq by the United States and her allies. Other plausible 'tertiary' effects of resource scarcity are famine and nuclear war, worsened by the protean manifestations of climate change and ecological degradation.

1.05.4 Ecosystem Services

There are several ways to conceptualize the relationship between human well-being, human health, and nature. The most common classification is that established by the Millennium Ecosystem Assessment, an international collaboration of more than 1200 scientists, collating and assessing relevant literature for a four-year period (2001–05). This group identified four main forms of ecosystem 'services': provisioning, culturally enriching, regulating, and supporting (Millennium Ecosystem Assessment 2003; Butler and Soskolne in press) (see Table 1).

The concept of ecosystem services is not universally accepted. A major criticism is that it is too human-centered; some ecologists prefer 'ecological functions,' probably because the word 'function' is perceived as less anthropocentric. In fact, association with economic terminology was deliberately undertaken in the hope that it would better convince economically rational policy makers that the benefits of ecological protection reached beyond that of nature conservation and protection to encompass and influence human well-being.

From an extreme biocentric (deep ecology) position, the intrinsic value of an algal bloom, jellyfish swarm, or school of cod may be considered proportional to its biomass; however, such arguments can merge with ecofascism and sophistry.

Provisioning ecosystem services refer to the functions by ecosystems, whether anthropogenic or largely free of human influence, that result in the material products desired and valued by humans, such as food, fiber, timber, and medicinal products. Some plants are used for dyes and other products for insulation, protection, decorations, and status. Examples include wool, hides, feathers, and shells. *Culturally enriching* ecosystem services have been partly discussed earlier. Elements include the knowledge and existence of charismatic species and the benefits to many humans that flow from contact with comparatively wild spaces. The third category is of *regulating* ecosystem services that produce benefits to humans and other species and are less recognized than provisioning services. Examples include the stabilization of slopes against erosion by forests and the cleansing of polluted water by passage through a filtering wetland. Another example is the regulation of Earth's climate by its global suite of ecosystems, a service now severely disrupted by human actions (see Vol. 4, Vulnerability of Ecosystems to Climate). Finally, *supporting* ecosystem services refer to functions generally hidden or invisible, such as the recycling of nutrients within soil by the actions of bacteria and billions of other organisms. Bacteria and other organisms living within the gastrointestinal tracts of animals, including humans, also perform poorly understood supporting ecosystem services. Provisioning and regulating services are discussed in more detail later in this chapter. Culturally enriching services have

Table 1 Typology of four ecosystem services, using a classification developed by the Millennium Ecosystem Assessment

Ecosystem 'service'	*Example*
Provisioning	Food crops (e.g., wheat fields, rice paddies, market gardens), fiber crops (cotton, bamboo), biofuels (e.g., from corn and sugar cane), animal products (e.g., sheep flocks, chicken farms), aquaculture ponds (fish stocks), freshwater, medicinal products (e.g., codeine, pyrethrum), mangroves (fish nurseries)
Regulating	Forests on slopes that stabilize soil, lessening erosion; coastal protection from storms and (partially) tsunamis (carbon stabilization); some cases of infectious disease limitation (e.g., Lyme disease, malaria in some cases, onchocerciasis)
Culturally enriching	Inspiration (charismatic landscapes and species, e.g., coral reefs, tiger reserves, old-growth forests), spiritual refreshment (sacred groves), religious observation, ancestral links, ceremonial decorations (red ochre, bird of paradise feathers)
Supporting	Soil fertility and nutrient recycling (microorganisms, earthworms, fungi), pollinators (insects, birds, bats), insect control (birds), seed dispersers (bats, birds, apes, elephants), detoxification, and nutrient recycling

Millennium Ecosystem Assessment, 2003: Ecosystems and Human Well-being. A Framework for Assessment. Island Press, 245 pp.

been discussed earlier, mainly in relation to psychological well-being. Some aspects of supporting services are now discussed in relation to biodiversity.

1.05.5 Biodiversity, Ecosystems, and Ecosystem Services

Biodiversity is a contraction of *biological diversity*, a term now about 30 years old, whose roots can be traced even earlier (Hutchinson 1959). Biodiversity and ecosystems interact with each other. For example, the distribution of species helps maintain ecosystems; intact ecosystems help conserve biodiversity. Ecosystems are in some ways analogous to information technology operating systems: species are the various files found on separate computers. Through competition, populations are generally kept in balance at a level their niche can support. Interruptions to important levers in maintaining this balance – such as loss of predators and other keystone species like carnivores and herbivores – can have profound effects on ecosystems. An example is the absence of predators because of extinction or absence, as can occur on islands, which is likely to lead to high populations of herbivores and consequent denuding of fodder, such as grass and shrubs. In some cases, this unchecked population increase can rebound to cause mass herbivore mortality because of starvation.

Similar phenomena can occur in the oceans, with nonlinear responses following an apparently small change. For example, variations in ocean temperatures have been predicted to alter many marine populations, including the sea star *Pisaster ochraceus*, which feeds on mussels. In turn, reduction in this keystone predator species reduces biodiversity, leading to an effective monoculture of mussels (Sanford 1999).

Disease can dislodge the ecological balance. An example is the epizoonosis (Epizoonosis is a disease that only affects nonhuman animals) rinderpest, commonly called cattle plague. In the late nineteenth century, rinderpest entered northeastern Africa via imported cattle and spread rapidly. This epidemic led to a massive loss of herbivorous animals, both wild and domesticated. With few animals grazing young tree saplings, trees took over the plains. Many farms were abandoned after the Black Death in Europe, which killed up to one-third of the population. Consequently, nature advanced. Forests reclaimed part of the landscape. Villages advertised for settlers to repopulate the districts.

Rinderpest, although it did not kill humans directly, also had profoundly adverse effects on human health. In the nineteenth-century African outbreak, loss of domesticated oxen reduced plowing and thus agricultural productivity. Infection in wild species lowered the effectiveness of hunting. Worsened by periodic droughts and exacerbated by smallpox, as many as one-third of the Ethiopian population and two-thirds of the Maasai people of East Africa died during a period still remembered by the Maasai as the *Emutai* ('to wipe out') (Gillson 2006). These cases also sound a warning over excessive genetic homogeneity. Deliberate breeding strategies can reduce resistance not only among animals, but also among plants.

There is a complex and as yet poorly understood relationship between biodiversity and ecosystem services (Lovejoy 1994). This speculation dates at least to Charles Darwin, although Darwin would not have used either term. It has been suggested that more biodiverse ecosystems have greater functional capacity, including for roles such as pollination, nutrient absorption, water purification, grassland productivity, and rice crop yields (Zhu et al. 2000). In some cases, diversity is beneficial because it leads to a greater likelihood of naturally occurring biological pest controls. Organic farming systems have a higher capacity to cleave protein and organic phosphorus and higher overall microbial activity than do the conventional systems (Maeder et al. 2002). Monocultures, in contrast, rely heavily on chemical pesticides and fertilizers, both of which can harm health (Hanna 2005). Monocultures are often preferred because of their generally higher yields (Maeder et al. 2002), yet their optimal performance requires favorable conditions and high-input agronomic systems. They typically do not perform well in marginal environments or without those external inputs of chemicals and fertilizers (Murphy et al. 2005). However, the specific biological mechanisms by which biodiversity influences many of these functions remain uncertain, and unfortunately, this has led to some resistance to value diversity for its own sake (Cardinale 2011).

In Western Australia, the brush-tailed bettong *Bettongia penicillata* improves the absorptive capacity of soil through its habit of digging for fungi (Garkaklis et al. 1998). Many species, including mammals, birds, and bats, assist in seed dispersal. Insectivorous bats are important regulators of insect populations. White nose syndrome, a devastating fungal disease decimating little brown bat populations in several northeastern states of the United States, threatens to increase the population of numerous insects, placing food security at further risk (Frick et al. 2010).

It has recently been recognized that some species of ants and termites have a similar function to earthworms in enhancing soil fertility. Their tunnels improve water infiltration, aeration, and soil nitrogen content. A recent field experiment has shown that the presence of ants and termites increased wheat yield by 36%. Such species may be especially important in arid climates (Evans et al. 2011).

Recent modeling work has shown that a process called 'niche partitioning' among species of algae can increase the uptake and storage of nitrate (Cardinale 2011), an important water pollutant. An implication is that biodiversity may buffer natural ecosystems against the ecological impacts of nutrient pollution (Cardinale 2011). Biodiverse ecosystems will also be more resilient to climate shocks than low-diversity systems.

1.05.5.1 Ecosystem Theory: History

The original scientific definition of an *ecosystem* as a basic unit of nature dates to 1935. Arthur Tansley coined this term, echoing the Russian scientist Vladimir Vernadsky (of whose work he was probably unaware) in appreciating that there is continual interaction between life and nonlife (the abiotic). Tansley also recognized that the boundaries between ecosystems are arbitrary but still useful for the analysis.

The *system* part of the term is linked to holism, synthesis, thresholds, phase change, emergence, and self-organization. Lovelock extended these ideas, conceptualizing the Earth system as a self-regulating, self-organizing entity in space (albeit with no planetary consciousness) (Lovelock 1979).

The idea of planetary homeostasis follows the nineteenth-century French physician Claude Bernard's recognition of homeostasis within a body. This is similar to the ancient Ayurvedic concepts of physical balance.

Recognition of the planetary impact of our species is fairly new, expressed by Nobel Laureate Paul Crutzen's call for declaration of the 'anthropocene' and its 'acceleration' (Steffen et al. 2011). Crutzen suggested that this new epoch started around 1750, at the dawn of the Industrial Revolution, when humans started to substantially alter the environment, by increasing the concentration of greenhouse gases, especially carbon dioxide (CO_2). Other gaseous and aerosol emissions also changed, as a growing population, assisted by unprecedented access to energy, formed a vastly altered landscape, by irrigation, deforestation, and grazing. Others have pointed out that humans have had large-scale impacts on the environment and its ecosystems for far longer, such as by the hunting and extinction of many forms of megafauna (Caro et al. 2011) and by deforestation and early farming (Caro et al. 2011; Ruddiman 2004). Previous academics also recognized the planetary scale of humanity's impact, including Marsh (1864) and Sherlock (1922).

1.05.5.2 Provisioning Ecosystem Services: Food

The consumption of organisms is essential to nutrition and health. Currently, the world produces enough food to supply adequate calories for about nine billion people, were this evenly distributed. In fact, roughly a billion people are classed as 'hungry' by the Food and Agricultural Organisation of the United Nations, while another two to three billion are recognized as micronutrient deprived, although they ingest sufficient energy and protein so as not to be grouped as 'hungry.' Climate change, in combination with other limits to growth, is likely to worsen food insecurity (Butler 2010a) (see 1.14, Climate Change Health Effects, Risks, and Impacts with Focus on Foodborne Diseases and Nutrition and Vol. 2, Vulnerability of Food Resources to Climate).

Human ingenuity, effort, and tools have radically transformed a substantial and increasing fraction of Earth's landmass and sea. Although hardly 'natural,' in this twenty-first century, most food is grown in these modified, anthropogenic environments, such as wheat fields, rice paddies, palm oil plantations, and fish farms. Intensive farming of both plants and animals appears inevitable if we are to feed the global population. However, others argue that the displacement of peasant farmers by corporations has greatly worsened food security (McMichael 2009).

1.05.5.3 Intensive Animal Farming

Billions of animals are raised and killed each year to feed people. Most of these creatures live in highly transformed ecosystems, sometimes called industrialized farms. Their conditions are kept from public view, helping to reduce community outcry. Living conditions for animals in such places are as little known to most people of the twenty-first century as the rat-infested slaughterhouses in Chicago, graphically described by Upton Sinclair in his 1906 book, *The Jungle*. Mainly grown this way are chickens, pigs, cattle, and several species of fish and shellfish. Small numbers of exotic mammals are also grown intensively, including racoon dogs and palm civets. There is increasing concern that intensively farmed animals can play an important part in the generation of unusually virulent zoonotic pathogens, such as highly pathogenic avian influenza (H5N1) and swine flu. There is also evidence that larger rather than small piggeries in Malaysia were associated with the 1997–98 outbreak of Nipah virus, a batborne pathogen, which killed more than 100 farmers and led to the culling of more than one million pigs. Ongoing pressures to further intensify farming practices to feed growing populations fuel this concern.

To date, most diseases associated with intensive farming have caused high animal rather than human mortality. However, high animal mortality, both through disease and control measures (to date, most notably for avian influenza, foot and mouth disease, and Nipah virus), can have substantial adverse effects on human health through loss of livelihood and the psychological trauma of culling animals, especially if they appear healthy (Zinsstag and Weiss 2001). Considerable anxiety remains that some of these diseases could affect humans in large numbers. Most anxiety concerns the possibility that highly pathogenic avian influenza (H5N1) will develop easy human transmission with high resultant lethality, although this is disputed (Palese and Wang 2012). Other concerns are for Sudden Acute Respiratory Syndrome (SARS), H1N1 influenza (the so-called swine flu), Nipah virus, and *Streptococcus suis*.

Intensive animal farming is also associated with a high climate impact in three main categories. First, the ongoing expansion of animals in 'landless farms' requires growing and shipping large amounts of feed, especially grain and soy. This stimulates the ongoing clearing of land, which also releases greenhouse gases, mostly CO_2. Second, digastric animals (cattle, sheep, and goats) release large volumes of methane (CH_4), a greenhouse gas that is far more potent per molecule than CO_2 (Shindell et al. 2009). The atmospheric life of CH_4 is much shorter than CO_2. Hence, a reduction in CH_4 emissions would lead to a fairly rapid decline in total radiative forcing, if other greenhouse gas emissions could be stabilized (Cox and Jeffrey 2010). Finally, the manure from animals releases large amounts of nitrous oxide (N_2O) (McMichael et al. 2007), which, because of its long atmospheric lifetime, is about 300 times more powerful than CO_2 on a per-molecule basis.

Digastric animals evolved millions of years ago and thus have released CH_4 for millions of years. During most of this time, atmospheric CH_4 remained at a constant level, but the human-driven, increased population of farmed digastric animals has contributed to a new CH_4 'plateau,' to which other sources, such as gas drilling, also contribute. Rice paddies are now a major agricultural source of CH_4. Similarly, these animals have always produced manure and N_2O, but the volume is much larger now. Eventually, if land clearing were to cease, the CO_2 emissions associated with it would stabilize, and then decline, as recovering, growing forests would absorb more CO_2 than emitted by the clearing of forest.

Stabilization of these emissions does not seem likely in the near future, given the pressure to feed the relentlessly expanding human population, which is increasingly demanding diets high in meat. Humans are converting a reservoir of biodiversity and ecosystems that provide mainly regulating services into provisioning ecosystems that grow large quantities of grain, soy, and palm oil (Danielsen et al. 2008). This effectively places Earth in a regulating services deficit. Unless corrected, this will initiate a cascade of events leading to a future Earth that is less likely to provide a habitat conducive for human civilization. Additionally, this transformation, unless slowed, will be accompanied by the extinction of numerous species, including many that humans regard as charismatic.

1.05.5.4 Other Provisioning Ecosystem Services

1.05.5.4.1 Biofuels

Human reliance on ecosystems extends far beyond food. Already, more than 5% of the global grain yield (mostly corn) is used for biofuel, mainly ethanol, a liquid fuel from plants. Although ethanol has low 'net' energy, its production is justified because it can produce a liquid fuel that complements oil and can be used for transport. In the United States, about 40% of the annual maize crop is used for ethanol, although a small fraction of the plant's energy is recovered as brewer's grain and used as animal feed. The use of other food crops for biofuel is also increasing, including sugar cane and palm oil. Australia is contemplating allowing the large-scale harvesting of forests, trees of which will be burned in power stations to produce electricity.

Biofuels require soil, water, fertilizer, farm machinery, labor, and effort to plant, harvest, and process. Most currently used biofuels compete directly with food crops, thus elevating food prices, which are already near a record peak. In turn, increased food prices add markedly to the risk of famine, poverty, and other drivers of undernutrition (Rawe et al. 2012). Indirectly, these stresses contribute to other forms of human insecurity, including insurgency.

1.05.5.4.2 Medicinal Products

On the positive side, the potential of yet undiscovered plants with therapeutic value is a powerful motivator to conserve ecosystems (Chivian and Bernstein 2008). In reality, the loss of indigenous people and languages and the erosion of other forms of indigenous knowledge mean that the identification of such substances is increasingly handicapped. In addition, the alleged pharmacological benefits of natural substances, especially body parts of animals, including some species that are endangered, have caused enormous harm to ecosystems (Graham-Rowe 2011). Examples include the harvesting of bile from imprisoned bears in China and trophy hunting of Mongolia's Gobi bears (*Ursus arctos gobiensis*), a species critically threatened with extinction. Pressures of rising population and increasing poverty continue to motivate many people to exploit whatever they can to survive. Another form of ecosystem provisioning service is culturally valued plants and animal parts that are used for decorations and status symbols, such as certain feathers, paws, and shells.

1.05.5.5 Regulating Ecosystem Services and Infectious Diseases

In recent years, a body of literature has appeared that argues that plentiful biodiversity and ecosystems can regulate (limit) infectious diseases. In reality, the relationship is rarely this straightforward (Butler 2008; Randolph and Dobson 2012). However, there are many cases in which ecological changes have altered and continue to change infectious disease epidemiology. This usually occurs in combination with human and climatic factors, including exposure to nature and public health measures, such as vaccine status and the use of insecticide-impregnated bednets. Examples are numerous. They encompass many vectorborne diseases, including Lyme disease, malaria, dengue fever, Japanese encephalitis, and onchocerciasis.

In other cases, however, ecosystem transformation has led to health improvements, such as filling of swamps, which reduces mosquito populations. Areas of intensely preserved biodiversity may be reservoirs of infectious agents, from Ebola to HIV. Many developed countries led the world in modifying their habitats; they generally enjoy high life expectancies.

1.05.6 Conclusion

The significance of the relationship between ecosystems and human health cannot be overstated. Good health requires healthy ecosystems. Ecosystems, of which humans are a part, generally have the capacity to sustain their own health; biodiversity is essential to achieve this. However, human population size and ever-intensifying manipulation of the environment have degraded most ecosystems, some to a critical level and others to collapse.

There is widespread denial about the extent, trend, and consequences of the relentless transformation of 'natural' ecosystems. Many highly transformed ecosystems risk critical degradation because of overuse, overgrazing, and contamination by chemicals, invasive species, and even landmines.

We conclude by discussing some of the factors required to emerge from the great danger that now confronts humanity and many other forms of life. To reduce the negative effects of climate change and fossil fuel depletion (Murray and King 2012), a range of technological strategies are emerging, although it is far from certain that these can be implemented at the required rate (Smil 2011). Slowing and reversing greenhouse gas accumulation is essential for human well-being, but far more than this is needed, and urgently so, too.

A range of nascent strategies exist for protecting some ecosystems. These include treaties and other international agreements to protect wild places (Antarctica, the Arctic, national parks) and wild species (charismatic animals). Other mechanisms include exchanges of 'debt for nature' (which seek to preserve large ecosystems) and legal agreements to offset carbon emissions in rich countries by protecting forests in developing countries, and in so doing, preserve biodiversity. To date, however, all such agreements share an ominous fragility. Even the ultimate protection of Antarctica must be considered at risk, especially to mining. The Arctic is also ripening for a mining and shipping boom, regardless of further damage to its ecosystems and to the global climate (see 4.39, Vulnerability and Adaptation in the Arctic).

Although more people and societies are awakening to the harms from ecosystem degradation, a decline in human well-being and the health of present and future generations appears inevitable if these trends continue. Although some Tragedies of the Commons (Hardin 1968) have been averted by regulation and cooperation (Buck 1985), this cannot be relied on, given the breadth and scale of current trends that lead to complacency. Many aspects of the global commons are worsening every year, and this deterioration seems likely to continue. Its prevention requires a vast amount of effort, exceeding that of the Space Race or World War II (Hoffert 2011).

Many barriers impede our collective capacity to change course. These include denial, the human capacity for adaptation, and recent apparent successes at extending human 'carrying capacity' (Butler 2004). A major cause for the erosion and loss of the many ecosystem services discussed at the start of this chapter is the displacement of most of the apparent harms and risks to a fraction of the global population that is far removed, conceptually and experientially, from those with more political and economic power. In this sense, the increasing destruction of the natural capital embodied in ecosystems is reminiscent of the destruction of English, Scottish, and Irish yeomen by the establishment of industrialization in nineteenth-century Britain. The Industrial Revolution generated unprecedented material abundance, but until social reform, it lowered the living standards and life expectancy of most of the British population (Szreter and Mooney 1998). The twenty-first century's ongoing loss of biodiversity and ecosystem services similarly threatens human well-being. Such effects are very unevenly distributed.

Several decades after its nadir in the early nineteenth century, life expectancy in Britain recovered (Szreter and Mooney 1998). Globally, life expectancy has not yet started to decline, although its rate of increase has unexpectedly slowed. The remainder of the twenty-first century is likely to determine our fate. A 'muddle-through' world could evolve, assisted by new price signals and energy technologies and a greater recognition of our indigenous nature (Butler 2010b) (see 4.35, Scenario Planning for the Future). That future may see improved well-being; if so, humanity will have learned not only that planetary resources are limited but also that other species and ecosystems warrant an enduring habitat on Earth.

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1.06 What Have We Learned about Climate Variability and Human Health?

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1.06.1 Introduction

The topic of human health ranks high among societal concerns (Cohen and Martinez 2010). In 2005, the United States spent $95 billion on medical research, with studies showing that Americans want more funds and resources devoted to health care and research (WHO 2009). Deteriorating environmental conditions are a major contributor to poor health and reduced quality of life, directly responsible for 25% of all preventable illnesses, specifically diarrheal and acute respiratory infections (DeNavas-Walt et al. 2010). According to a recent report by the World Health Organization (WHO), approximately 7% of deaths and diseases around the world occur because of inadequate or unsafe water, sanitation, and hygiene, and an estimated 5% of deaths and diseases are due to air pollution (WHO 2009). Extreme climatic events, such as floods, earthquakes, and droughts, also increase the risk of diarrheal disease and outbreaks of vector-borne diseases. Such extreme events threaten not only the individual's health but also access to health care. In Pakistan, for example, more than 200 health facilities were destroyed or damaged by the flood of historical proportion during the summer of 2010 (Stedman 2010). The aftermath of the Pakistan's flooding includes the rise of communicable diseases – acute respiratory infections, diarrhea, and skin infections, as well as cases of malaria – prompting the need to develop a larger adaptive capacity as well as strengthening the current public health response.

Where increases in temperature and precipitation have occurred, they have contributed to an increase in vector-borne diseases, particularly dengue fever. The incidence of dengue increased 30-fold since the 1960s, spreading in geographic scope and from urban to rural communities where health care may be less accessible (Fouillet et al. 2007). In addition to higher average temperatures, the number and intensity of heat waves could increase as a result of variability and change in weather patterns. The 2003 summer heat wave in Europe showed how the rich and poor worlds are equally vulnerable to nature. Those with a weak adaptive capacity were at risk, such as the population subgroup with respiratory and cardiovascular disorders and the elderly children.

The effect of extreme climatic conditions cannot be minimized (Trenberth et al. 2000). Extreme weather events include precipitation extremes, severe storms, heat waves, and flooding and have caused many deaths and injuries each year in the United States and around the world. Changes in weather patterns would alter the timing, frequency, length, and intensity of extreme events (Greenough et al. 2001). Increases in heavy precipitation have been reported over the past century (IPCC 2007). The severity of such changes is also related to the reliability of one's health care infrastructure to support such events, as well as its accessibility. For example, in Pakistan, approximately15 million people were affected during the flood of 2010. Again, clean water and sanitation were scarce. Many millions needed health care assistance, especially those affected by communicable diseases such as malaria; however, owing to the flood waters more than 200 hospitals and clinics were damaged or destroyed, limiting access to health services. Weather patterns play a key role in influencing natural ecosystems as well as the human systems that are dependent on them. Because many entities are tied to climate, any variability in climate has far-reaching effects, such as human and animal migration patterns, food production, water availability and use, and health risks. Warmer average temperatures combined with increased variability would alter the pattern of exposure to thermal extremes and resultant health impacts in both summer and winter (WHO 2009). According to the WHO, in developing countries, approximately 2.4% of diarrhea and 6% of malaria cases are caused as a result of water contamination during time of floods.

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In the following section, the authors review the salient research that outlines the concept of and factors that contribute to society vulnerability. This section also reveals the concerns surrounding vulnerability and climate variability and long-term change and its impacts on human health. In Section 1.06.3, the authors detail the implication of climate in human health. Just as it is imperative to understand the impact of climate in health outcomes, it is also vital to discuss the role of public health systems in reducing social vulnerability to climate. Likewise, it is also important to discuss how vulnerable regions and society provide a focus of new research, resulting in additional knowledge that is relevant to the needs of society with different social, cultural, and environmental conditions. Sections 1.06.4–1.06.6 will show the complexities involved in the analyses of climate and its effects. After a brief discussion of methods, the authors explore the literature on the human health consequences, both indirect and direct, as a result of climate, and how the issues surrounding climate are complex and dynamic. In the final section, the authors justify the rationale for different levels of thinking and planning that are required for improving the social consequences of climate.

1.06.2 Social Vulnerability to Climate and Other Ongoing Changes

Vulnerability, within the context of health, can be expressed as one's susceptibility to shocks emanating from climate and other factors. Vulnerable populations include those at risk of poor physical, social, and/or psychological health, and there are groups of people who have a higher probability of becoming ill (Shi and Stevens 2005). There are a variety of determinants of vulnerability, including homelessness, poverty, disability, chronic illness, age, gender, social status, low income, and lack of education. The effects on human health from these events include physical injury, increased exposure to disease pathogens and/or their vectors, exposure to airborne allergens and chemical releases, nutritional deficiencies caused by food shortages, and psychosocial and mental health outcomes associated with loss, disruption, and displacement. Those in low-income countries may be more susceptible to heightened exposure to infectious disease (endemic waterborne, insect-borne, rodent-borne, and food-borne diseases) because of compromised water and sanitation systems (Cutter 2006). Environmental variability at various levels can result in intensifying vulnerability to the health impacts. These environmental changes alter the probability of human exposure to hazards as well as people's susceptibility to their impacts (Few 2006). A major concern is the impact that extreme events could have on health care systems. Without the institutions and services whose role is to protect and help maintain health, a society's ability to recover would be greatly hindered. People who are poor and lacking in education may wait too long and have less access to health care. Those with little or no income may not have the time or financial stability for preventative health measures (Adger 2006). Floods and windstorms can damage these institutions during times when they are needed the most.

Impacts on society are not just shaped by physical forces alone. For example, during and following a flash flood, the consequences can range from direct physical injuries to psychosocial effects of sustained exposure to flooding events (Few 2006). Hazards much like flash floods can have an interactive effect on health, for example, the links between inadequate nutrition and disease susceptibility, and mental health and indisposition (Shi 1997). Many of the events discussed within the literature include floods, windstorms, wildfires, and droughts. Extensive fires in forest areas have the possibility of causing and exacerbating respiratory problems worldwide. Increased drought can result in the worsening of the effects of malnutrition and risk of disease in Africa (Few 2006). The vectors of disease-causing organisms may shift to other locations as a result of rising temperature. There are a multitude of factors that may intensify vulnerability to the health impacts of environmental hazards. If, for example, surface vegetation changes are substantial, the potential for drought and loss of mangroves in coastal areas increases; this may lead to a loss of natural protection against waves during storms (Few 2006). Vulnerability can be considered a combination of social factors and physical factors. The former deals with a population's susceptibility to impacts, whereas the latter refers to the probability of physical exposure to the event.

Social vulnerability varies depending on the behavior of and the resources available to the population (Few 2006). The concept of 'coping capacity' is intertwined with social vulnerability; how well can people avoid infection and how robust is the health care infrastructure to continue running during an extreme event? In addition, vulnerability includes two factors, 'external' and 'personal.' What is the person's current health status, mental health status, and nutritional health status? These aspects can influence an individual's vulnerability to illness. Each person has characteristics, either inborn or acquired, that interact with the environment and influences health (Rogers 1997). According to Rogers (1997) these characteristics may include temperament, genetic predisposition to disease, drug sensitivity, and susceptibility to illness. Acquired characteristics may include life experiences and learned abilities such as coping skills. These factors may affect the individual in his/her response to stress events. External components of vulnerability include a person's immediate environment as well as the individual's family and community. It is important to note that the full scope of health impacts and the complexity associated with them extend beyond those mentioned in this chapter. The following paragraphs discuss the vulnerability associated with population and climate.

1.06.3 Climate and Human Health

Although early discussion on climate effects and human health mostly focused on heat stress, infectious disease, and extreme weather events in specific regions, recent studies are beginning to evaluate the social, economic, and demographic factors in relation to health risks. The evolving discussion on climate and human health can be seen in two overlapping but distinct phases. The first phase, where the more early literature is placed, is characterized by the limited scientific literature on health impacts as a result of climate. Predictions that vector-borne diseases such as malaria could spread to other locations as a result of changes in weather patterns were a significant part of the discussion within the early research (Ropelewski and Halpert 1986). The idea that water quality could be potentially affected as a result of heavy rainfall, leading to contamination, was also addressed (Cook 1992). Increases in temperatures were reported to likely change the prevalence or intensity of asthma and allergic disorders (Hulme 2009). On a lesser scale, psychological disorders such as depression and anxiety have been hypothesized to increase. Increases in climate variability may alter temperature and rainfall patterns, disrupting practice of agriculture and supply of water resources, leading to malnutrition especially in vulnerable populations (Confalonieri and Menne 2007). Because of the limited scientific research available during the first phase, the effects on human health are reported as 'likely' or 'possible' to occur. While scholars continue to unravel the link between illnesses and seasonal trends in temperature and rainfall (Persinger 1980), much of the research in this phase concentrated on heat- and cold-wave episodes.

Within the second phase, characterized by the increased confidence of the effects of climate on health, focus shifts to the role of public health and adaptation responses in these later articles (Fouillet et al. 2007). For example, climate has been found to be a more important determinant of life expectancy in African countries (developing) than in non-African countries. While climate is important in determining both life expectancy and income, the latter can also play a part in tempering the negative impacts of climate on life expectancy (Schar 2004). This is to say that climate conditions that lead to warmer temperatures and drought and floods may lead to developing countries remaining trapped in underdevelopment of health (Kovats et al. 2003). The role of public health and climate has become an important part of discussion to date, whereby vulnerable regions provide a focus of new research, resulting in additional literature. Along with revealing the complex interactions behind climate and human health, adaptation methods are also being developed to lessen the effects of climate on health.

1.06.4 Water and Human Health

More than a billion people live without access to freshwater. Water can be seen as an indicator of health, as it is clear that without access to potable water survival chances are lowered. Half of the world's people are living in areas where water tables are falling, including China, India, and the United States, who are the biggest producers of grain (Brown 2008). Water scarcity is reported to affect one in three people in the world. Population growth, urbanization, increases in industrial and household uses exacerbates the problem. Along with quantity, quality of water is equally important. A variety of different microorganisms can affect the quality of a water supply. The most common microbes found in water are bacteria, protozoa, viruses, and helminthes. Some of these pathogens may be found naturally in the water supply, and others may be introduced into the supply through human and animal waste contamination (McMichael et al. 2003). Bacteria can be found naturally in both groundwater and surface water. Pathogenic bacteria found in water supplies generally come from human and animal waste (Arnell et al. 1999). Protozoa are found usually in oceans, rivers, lakes, ponds, and other aquatic habitats. Protozoa have the capability of making their way into groundwater from the connection between an aquifer and surface-water source through compromised wells or springs (Kovats et al. 1999).

Inadequate safe drinking water and a poor health care infrastructure, as well as lack of access to health care providers, as in the aftermath of the Haiti earthquake in 2010, can put human health at risk. Cholera, as with many other infectious diseases, is transmitted primarily through consuming contaminated drinking water or food. An outbreak of cholera followed the devastating earthquake in January 2011. The outbreak began in October 2010, and by March 2011, approximately 4672 people died (Walton and Ivers 2011). Cholera had spread to all of Haiti's 10 provinces by the first week of the epidemic. Since then, cholera has spread to some of the neighboring countries, including the Dominican Republic and Venezuela. Because many of Haiti's residents are unfamiliar with cholera, and without a strong public health system, there are many misconceptions about the disease. According to Doctors Without Borders (2011), for example, some may choose to stay away from the treatment centers for fear of having the centers in their neighborhood because they believe it helps to spread the disease; however, the opposite is true, it is more beneficial to one's health to have a treatment center close to the population. The importance of a proper health care center is a key factor; cholera treatment centers must allow for patient isolation to ensure effective treatment. In the United States, *Vibrio vulnificus* infections were identified by health officials in evacuees from New Orleans as a result of the flooding from Hurricane Katrina (Bopp et al. 2005).

Many pathogenic viruses and helminthes, like pathogenic bacteria, are introduced to water supplies from human and animal waste contamination as well (Arnell 1999). Symptoms vary and can include cramping, vomiting, diarrhea, fever, dehydration, abdominal pain, chills, nausea, fever, coma, loss of appetite, severe weight loss, fatigue, jaundice, dysenteric or urinary symptoms, itching on skin and dermatitis. Heavy rainfall events are one consequence of climate variability, which directly impacts water availability and quality. Literature shows an increase in the number of outbreaks of waterborne diseases as heavy rainfall events increase, suggesting a scientific consensus that the progression of climate variability has an overall negative impact on water quality (Bilham 2010).

1.06.5 Human Health, Food, and Nutrition

Higher temperatures (within a range) increase replication cycles of food-borne pathogens (Rose et al. 2001). Food-handling mistakes may be more prevalent in prolonged seasons. In the United States, these diseases cause approximately 76 million cases of illnesses, with 5000 deaths per year (Newell et al. 2010). As a public health issue, a large number of food-borne illnesses are reported and are associated with economic costs. Pathogens like salmonella multiply at room temperature. The WHO Surveillance Program for Control of Foodborne Infections and Intoxications in Europe indicate that 32.5% of outbreaks are a result of time–temperature abuse. A study done in Australia reported an association between increases in salmonellosis infections and increased temperature (Tirado and Schmidt 2001).

Climatic factors, particularly precipitation and temperature, are closely related to food-borne illness. Those who rely on marine-based diets may be at a greater risk, as weather variability has been associated with coastal water contamination and shellfish-related diseases (Miraglia et al. 2009). *Vibrio* spp., and the diseases caused by the species, is strongly manipulated by climate factors, especially temperature. In more subtropical regions, this pathogen thrives. Salinity also plays a large role in its survival. Another example of how weather has the potential to influence food-borne diseases is through the transmission of *Cyclospora cayetanensis*, which causes diarrheal disease (Newell et al. 2010). The growth cycle and maturation of this protozoan consists of a process called sporulation, which is dependent on warm temperatures. Studies have shown that this protozoan has a distinct seasonality that peaks in the summer months (Miraglia et al. 2009).

Crop pests such as locusts, aphids, and whiteflies can thrive in dry environments and can spread a mold that makes aflatoxin, a substance that may aid the development of liver cancer in those that ingest contaminated corn and nuts (Rose et al. 2009). Researchers believe that climate variability and change may ravage crops that are already stressed, which would worsen malnutrition and poverty and fuel human migration. If agricultural pests and weeds spread, and there is increased use of toxic pesticides, farm workers and their families could be harmed (Newell et al. 2010). Agricultural crops and fisheries may be compromised as a result of runoff and toxic spills released into the environment from extreme weather events due to climate variability and change (Newell et al. 2010).

1.06.6 Heat Waves

Heat can be a natural hazard. High temperatures can bring about symptoms of heat stroke, heat exhaustion, heat syncope, and heat cramps (Kovats 2008). Severe heat stroke is defined as core body temperature exceeding 103 °F and dysfunction of multiple organs. The progression to death from heat stroke can be a matter of hours, while survivors may have permanent damage to organ systems. Although the phrase ‘heat wave’ does not have a universal definition, they are considered extreme events that are associated with continuous, hot temperatures that can be fatal to humans (Meehl 2004). Examples include the 1995 Chicago heat wave, the European heat wave in 2003, and more recently the Australian heat wave. In each instance, human health and well-being suffered. From past heat wave events, health risks have become evident. In the case of Chicago, more than 500 heat-related deaths were reported. As all heat waves are considered preventable, the lack of preparedness was evident. In the European heat wave of 2003, more than 30 000 excess deaths were reported, with approximately 2000 deaths occurring in Paris. Because the heat wave occurred during the holiday season, the heat stress was exacerbated by the lack of hospital staff.

The heat wave that Russia experienced during the summer of 2010 is an example of potential impacts of climate on human health. The heat wave killed approximately 11 000 people in the city of Moscow, helped spread wildfires, and took out more than one-third of the country’s grain harvest, which drove up food prices globally. Climatologists in Russia noted that no similar event had been recorded in at least a thousand years; however, more recent studies disagree that it was so unprecedented (Dole et al. 2011). The extreme temperatures were due to a major high-pressure ridge that stopped the normal movement of cooling storms that come from the west, which allowed warm air to flow north from the tropics. These anomalies are common and result from natural instances; however, the intensity of the occurrence over Russia was unusually strong. Because of the complexities behind the science of blocking events, more research is needed to determine the role of climate variability and change in these events.

In 2009, many regions in Australia reached record temperature highs. The heat wave exacerbated fire conditions during the 2008–09 Australian bushfire season, causing many bushfires in the affected region and leading to the Black Saturday bushfires, which killed 173 people in Victoria (Nitschke et al. 2011). Many people, a majority being elderly, were treated for heat-related illnesses. In addition, many homes and businesses lost power for days. Railway lines were stopped, and many acres were destroyed. The state’s power supply also collapsed as many residents tried to use air conditioning. In a matter of barely 3 days, Hurricane Mitch in 1998 brought some 6 feet of rain on Central America. In the ensuing days, the incidence of malaria, dengue fever, cholera, and leptospirosis soared (Epstein 2005). In Mozambique, three cyclones inundated the country for 6 weeks in 2000, whereby the incidence of malaria rose fivefold. These cases are clear indicators stressing the need for a strong response and recovery unit within a working public health system (Nitschke et al. 2011).

While many heatstrokes result from activity in hot weather (e.g., working outdoors, playing sports), in the case of individuals who are less fit, these heat illnesses can occur even when performing low levels of activity. This is due to the low cardiovascular reserve associated with lack of exercise, which leads to low heat tolerance. There is a clear limit to which the human body can tolerate heat. From studies done in Saudi Arabia, evidence has shown that after a severe heat wave, heat stress proteins were created and reactions of the immune system were significant in causing deaths (Bouchama 2002). Humans do have the capacity to adapt to changing climates and environments. We have seen differences among cultures in physiological, architectural, and behavioral aspects because of differences in climate. People who live in warmer climates have been shown to have higher thresholds to hot weather, in terms of adaptability. Examples of this include those who have moved to hotter countries, including soldiers and athletes. This physiological adaptation takes place over a few days to weeks. The body’s response is to increase the number of sweat glands and improve cardiovascular stability to heat exposure. Behavioral changes also play a part, including clothing, diet, activity, and drinking (McGeehin 2001). Heat waves occur in all countries; however, some countries are more vulnerable than others. The two main reported groups of people at highest risk are young children and the elderly. It is the changes in the thermoregulatory system that makes elderly people more vulnerable to heat (Meehl 2004). Children and babies also have a higher risk of dehydration and lower thermoregulation capabilities.

1.06.7 Vector-Borne Disease

The relationship between climate and infectious diseases has been studied for centuries. In his 1840 treatise *On Miasmata and Contagia*, Jacob Henle stated, "Heat and moisture favor the production and propagation of the infusoria and the molds, as well as the miasmata and contagia, therefore miasmatic-contagious diseases are most often endemic in warm moist regions and epidemic in wet summer months." He noted cholera and yellow fever among the miasmatic-contagious diseases, and today, as global warming continues, these diseases may resurge. There are three different components working together: the vertebrate host, the invertebrate vector, and the parasite (bacteria, viruses, etc.). Each part is responsive to environmental changes in different ways (Patz and Reisen 2001). Increased temperatures generally speed up the development of both vectors and pathogens and can lead vectors to bite more often (increasing transmission rates), but higher temperatures, above a respective threshold, can cause higher vector deaths (lowered transmission rates). In the highlands of Africa, cool temperatures limit malaria parasite development; if temperature continues to increase, malaria transmission may increase as well (Githeko et al. 2000). In addition, St. Louis encephalitis viral replication and length of transmission season are dependent on temperature; 'snowbirds,' the migratory, nonimmune elderly population of southwest United States, would be at higher risk if they arrive in early fall to stay for the winter months (CDC 2011a). Also, dengue fever transmission season may be prolonged if aided by warmer temperatures (CDC 2011b).

1.06.8 Methods

For the purpose of this chapter, the authors applied bibliometric analysis to understand the trends in climate variability and human health discourse. Following Neff and Corley (2009), coword analysis was applied (i.e., words most commonly used together in titles, abstracts, or list of keywords). The theory of coword analysis is taken from the idea that research areas can be characterized and analyzed from patterns of keyword use in publications. When new concepts and ideas are put forward or the community accepts new methods, the keywords that stand for the concepts allow for subsequent authors to build upon the idea (Neff and Corley 2009). For the scientific literature, relevant reports and publications were identified from electronic reference database using combinations of keywords of 'climate change' and 'health.' Climate change, although a nebulous construct, was used since this is the phrase most commonly used when referring to climate variability.

When examining specific topics within climate variability and health, a combination of keywords were used that were developed from the health outcome categories, limited by date. The following databases were searched: Medline, BIOSIS, Web of Science, and CSA Illumina social sciences index. Results of individual searchers were filtered using a series of Boolean pairings. In each of the database searches the option for full document was searched for the keywords. Only English articles and publications that appeared to provide information on the impacts of climate on health were analyzed.

If the abstract suggested that a publication might provide useful information, or the title or keywords supported such a conclusion when an abstract was unavailable, the publication was obtained and reviewed. When examining the discussion of the role of physicians in climate and health, the following medical journals were analyzed: *British Medical Journal, Journal of the American Medical Association, The Lancet, and New England Journal of Medicine*. Google Scholar was used to search within the specific journals. Duplicates were filtered out using RefWorks, which identifies duplicates and allows the user to delete unwanted articles. In analyzing the news media, the Proquest historical newspaper database was used to search the New York Times as well as Google News. For both, the earliest relevant articles began in 1985. In addition to overall content, front-page stories were also examined.

1.06.9 Results and Discussion

1.06.9.1 Surge of Publication: Bibliometric Analysis

Understanding the effects of climate variability and change and preparing for future events is important for public policy in health. In turn, a strong public policy is necessary to ensure safety. The summer of 2003 was reported to be the hottest in Europe since, at the latest, AD 1500 (Stott et al. 2004), although Chase et al. (2006, 2008) and Connolley (2008) show that, in the global context, such extreme heat waves are not unusual. This resulted in unusually large numbers of heat-related deaths in several countries in Europe. A French parliamentary inquiry stated that the health impact of this event was unforeseen. In addition, this event revealed weaknesses in the surveillance for heat wave deaths, the lack of knowledge leading to an inadequate public health response, and the limited strength of public health agencies as well as the lack of communication between public organizations (Fouillet et al. 2007). Following this heat wave event, the literature increased substantially (**Figure 1**). The content consisted of determining the cause of the heat wave to be in some part due to anthropogenic climate change, as well as discussing ways to prevent deaths and injury if and when similar events occurred and ways to fix the weak points in the public health system. Similar outcomes have been seen for other extreme events such as Hurricane Katrina, which revealed the shortcomings of the Federal Emergency Management Agency (FEMA) (Brodie et al. 2007).

1.06.9.2 Absence of Physicians in the Discussion of Climate and Health

Although there is a call for the participation of physicians, there is notable absence of them in the debate of climate and health. A physician's opinions can have credence to the general public as has been reported by Sarfaty and Abouzaid (2009), who found that physicians are the most trusted source for health information. This could help build public consensus that is needed at a time when climate variability and change has become a political polarized issue (Mitchell et al. 2002). The role of the doctor has yet to be clearly defined within the climate and health discussion. The literature presents multiple ways in which physicians could potentially address the nexus

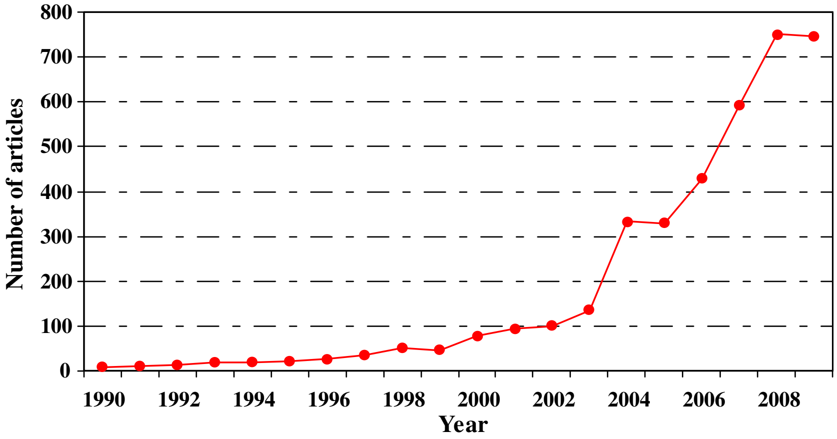

Figure 1 The number of articles from 1990 to 2009 discussing climate variability and heat waves. The circled point indicates when the 2003 European heat wave occurred.

between human health and climate (Sarfaty and Abouzaid 2009). In clinical medicine, climate variability and other environmental stressors are already causing patients in particular regions, certain ages, or with certain medical conditions to seek clinical care. In addition to clinical medicine, reducing carbon emissions in the workplace, using communication outlets to educate patients and the public, using surveillance means to identify conditions related to or caused by climate, and public policy are other contexts in which physicians can get involved (Sarfaty and Abouzaid 2009). As experts in their field, physicians are often called upon to impart health knowledge to aid the public.

1.06.9.3 News Media, Health, and Climate Variability and Change

Americans still think mostly about ice caps and polar bears when climate variability and change is mentioned (Sarfaty and Abouzaid 2009). The number of 'climate skeptics' is greater in the United States than in any other country. Scientists and lay public differ sharply about their views on climate variability and its causes. A Pew Research Center (2009) poll found that 84% of scientists believe that the Earth is getting warmer because of burning of fossil fuels, whereas just 49% of the US public held this view. Several factors may be contributing to this difference in the understanding of climate variability, with media being the important one. For most lay people around the world, and certainly in the United States, exposure to climate science has been almost entirely from general media and not from climate scientists (Weber and Stern 2011). Media reporting, as we all know, follows rules different from those of scientific reporting, whereby maximizing audience share and conforming the value of the media outlet's owner is the primary goal of the media (Hulme 2009). Even though there is a general consensus of anthropogenic influence, media depictions often are too dramatic and dividing and are more pervasive in the United States. It is primarily through the media that climate variability is represented publicly (Carvalho 2007; Weber and Stern 2011). Scientific knowledge is also used by other entities, including activists and businesses, to justify certain actions or campaigns. Thus, as new pathways between the citizens, politicians, media, and scientists are established, the ties between science and politics have gone public and therefore welcome more criticism and evaluation (Boykoff 2007).

Although there is a general consensus, there are still many aspects within climate variability (and especially within climate variability and health) that are labeled 'uncertain' because of the complexities involved and additional studies required. This

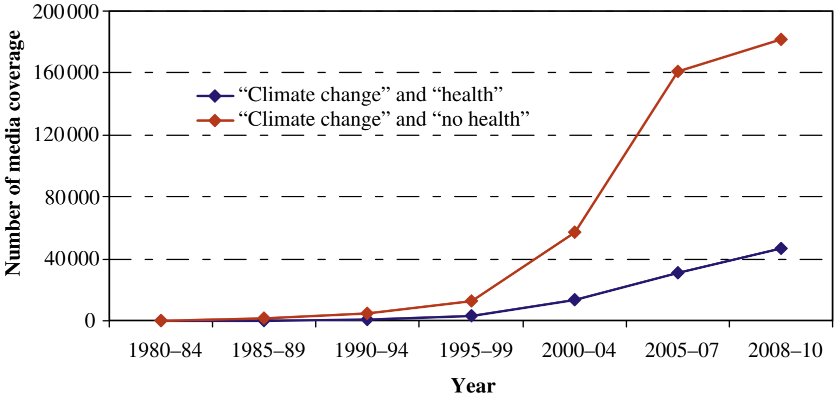

Figure 2 Articles discussing climate variability and health versus climate variability and topics other than health.

'uncertainty' becomes an issue in journalism; in many reporting situations, journalists avoid abstract storytelling (Weingart et al. 2000). This may lead to the climate variability dimension aspect being cut out of a story, if it is too uncertain. On the other hand, journalists may narrow their focus regarding climate variability-related issues, depending on what they see as 'the story.' For example, the story may be found in the visual nature of a flood and other extreme weather events or may be politically relevant, resulting in losing the long-term picture of the bigger issues (Boykoff 2007). While Americans rank climate variability and change as a low-priority issue, it is interesting to note that climate risk perceptions, behavioral intentions, and policy priorities shifted significantly following the release of *The Day After Tomorrow* (Leiserowitz 2004).

In terms of climate and human health, it appears that the majority of the discussion is not directly health related but stems from elsewhere (mostly an integration of politics of climate change) (Figure 2). For example, in President Obama's new vision of a US energy economy, "[We can] pass comprehensive energy and climate legislation that will ignite new industries, spark new jobs in town like this [Iowa] and make America more energy independent" (Leiserowitz 2004). In general, although human health is generating some discussion within climate-related news, an overwhelming majority belongs to topics other than health-related issues.

1.06.10 Conclusions

In tracing the information presented in the academic literature, the implications of climate variability and long-term change are significant for human health, which in turn calls on public health action. This chapter concludes that the discussion on human health and climate has evolved and the human health link established. The topics of water- and food-borne diseases within the nexus of climate and human health discussion are two examples of how altering the physical environment can lead to a range of human health effects through water stress and waterborne diseases; water management and policy are also affected. In the discussion on human health and climate, there seems to be a handful of authoritative figures that the public and politicians can turn to for information, physicians and the public health sector, the news media, and the scientists. In order to be most effective, it may be necessary for the interdisciplinary dialog to be strengthened between these three sectors. Although new pathways to the same health risks through climate variability and change are being highlighted, the message has stayed consistent since the beginning; inadequate action has been taken even with the increase in knowledge of the effects of climate variability and change. One possible action may be, once an interdisciplinary team is formed, to start within the United States and to inform and train other officials and health professionals about the health risks from the effects of climate variability and change. This model may then be taken to other countries that are more vulnerable to start a similar interdisciplinary sector. However, it may be more difficult to start within the United States, as the population has not had much interaction with health and climate interaction, versus within a region where the effects are clearly evident and where the population is more apt for action.

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1.07 Food, Nutrition, and Public Health

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1.07.1 Introduction

The aims of this chapter are to describe the threats and risks to human health related to the impacts on food and nutrition, of environmental factors including those consistent with climate change and to demonstrate that global and regional strategies will be needed if adaptation and mitigation measures to reduce negative health impacts are to be effective, especially in developing countries, where the burden of ill health is already high. The climate factors that influence food and nutrition directly are heat waves, extreme weather events such as floods, sustained daytime and nighttime temperature rises, increased precipitation, and drought. Indirect impacts are also likely from changes in agrosystems and hydrology and disruptions of natural ecosystems and their effects on plant pests and disease (World Resources Institute 1998-1999), as well as socioeconomic and demographic factors attributable to climate.

1.07.2 Malnutrition

Epidemiological studies have shown that deficient intakes of energy, protein, or micronutrients are associated with ill health and increased mortality (Van den Broek 1995). The relationships between food insecurity, malnutrition, morbidity, and mortality are well documented (Young and Jaspars 2009). A major study stated: "Multiple biological and social factors affect the incidence of malnutrition but one of the fundamental determinants is the availability of staple foods. Climate variability may affect this…" (McMichael et al. 2004). However, malnutrition has its biggest impacts in populations where mortality levels are already high. It is already obvious that food insecurity and poor nutrition are distributed unequally between regions and countries. For example, a 2009 report showed that in India, 37.4% of females and 39.4% of males suffered from chronic energy deficiency, with undernutrition most serious among rural and the most deprived populations (Government of India Ministry of Environment and Forests 2009).

Immunologic defenses are impaired in malnutrition, and hence, infections tend to last longer and are more likely to lead to complications. Severe anemia and severe bronchopneumonia resulting from malnutrition are frequent causes of death in children in some developing countries. In countries where temperatures fall drastically at night, malnourished people risk death from hypothermia. These effects tend to be worse among the most deprived populations, and more so among girls, as they are compromised by poor access to health care, lack of education, and preferential concern for the health of male children (Van den Broek 1995).

The relation between malnutrition and mortality is exponential – in a worsening nutritional crisis, malnutrition and mortality increase in a curve that becomes steeper (Young and Jaspars 2009). Food insecurity is also associated in developing countries with stunting of children 0–24 months, while severe stunting is associated with a longer term mortality risk in the same age group. Stunting is associated with greater child mortality and also has medium and long-term impacts such as cognitive impairment, poor school performance, decreased work capacity, and increased risk of adult morbidity and early death (Young and Jaspars 2009). The effects of undernutrition are considered to span at least three generations. The prevention of stunting requires population-wide interventions, preferably before conception. Malnutrition also contributes to a range of diseases: underweight is documented as an underlying cause of child deaths associated with diarrhea, pneumonia, malaria, and measles (Young and Jaspars 2009). Also, most child deaths in developing countries result from disease made worse or aggravated by malnutrition.

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Despite significant achievements during the past century, gender inequalities continue to shape the daily lives of many women worldwide and put them at greatly increased risk of adverse health impacts due not only to climate variability (Blomstrom et al. 2009) but also the prospect of longer term climate change. Women are the main producers of food especially in the developing countries, and yet own less than 15% of land (UNFPA 2009). When financial assistance or investment is available for agriculture in developing countries, women farmers tend to receive only a small a fraction of it (Chen et al. 1981), so that they are likely to be more disadvantaged in recovering from the adverse effects of climate variability. Women and girls in developing countries are also more likely to be malnourished than men and boys, since male household members generally consume more calories and proteins and may receive better health care than females, at all ages. Women and girls also have the biggest decreases in food consumption in the aftermath of climatic disasters including drought (Sivakumar and Kerbart 2004; Oxfam International 2005).

1.07.3 The Impacts of Social, Environmental, and Economic Determinants on Food, Nutrition, and Public Health

The proportion of people, worldwide, reported as hungry (i.e., with insufficient intake of food energy) by the Food and Agriculture Organization (FAO) plateaued at about 16% between 2000 and 2007, before rising. This trend, set against the context of the global economic crisis and rising food prices, has led to the conclusion that the Millennium Development Goal to halve, between 1990 and 2015, the proportion of people who suffer from hunger may be difficult to meet in many regions of the developing world (United Nations 2011), where an interplay of environmental, economic, and social factors expose the population to the risks of poverty and malnutrition (Lipton 2001). Several manifestations of local and regional climatic change would exacerbate these risks (Warren et al. 2006), especially in communities with higher levels of vulnerability and low adaptive capacity, and need to be considered within a common and integrated framework of environmental determinants of health.

Conventional assessments of risks to human health have focused on hazards whose magnitude can be measured and on determining dose–response relationships between levels of exposure and impact on human health (Patz and Balbus 1996). However, the health impacts of climate effects on food and nutrition are mediated through a complex spectrum of ecological and social variables, including the underlying socioeconomic and demographic vulnerability of the population. This requires the development of integrated models of risk assessments. This also necessitates the development of flexible adaptation strategies at regional and community levels, with governments, industries, and communities working together to monitor changes and establish support systems to improve the coping capacity of populations. These should help food growers adapt to a range of possible climatic scenarios and help the most vulnerable populations avoid the worst effects of food and nutrition problems. However, as this chapter explores, the impacts of climate occur within powerful global economic and trade systems. The regions where the largest negative health impacts are likely to occur are those most constrained by poverty and lack of power and development, and are thus least able to adapt. The climate effect on developing countries' crops and aquaculture occur within social, economic, and environmental factors that are often dictated by economic, trade, and aid policies and conditions outside their influence. Hence mitigation of the largest negative impacts of climate change on food, nutrition, and public health has to be addressed globally as well as at regional, state, and community levels.

1.07.4 Food Security

Food security occurs when all people, at all times, have physical, social, and economic access to sufficient, safe, and nutritious food that meets their dietary needs and food preferences for an active healthy life (FAO 2008). Agriculture and fishing produce the world's food supplies. Changes in temperature and rainfall and extreme weather events (Antwi-Agyei et al. 2012) would likely have significant impacts on agriculture and on fish stocks via sea temperature change. Hence, these changes can impact on food security, which is inextricably linked to nutrition and health as well as economic development, environmental sustainability, and trade.

Many countries lack food security, and the food and nutrition needs of most of their populations are precarious. The International Fund for Agricultural Development (IFAD) (2002) estimated that the basic daily needs for sufficient food of 1.2 billion people around the world are not met. About 800 million of them live on marginal land in rural areas and depend on rain-fed agriculture that is susceptible to disruption from climate (Ludi 2009). In developing countries, the pressure from rural poverty – increasing numbers of people trying to make a living out of decreasing resources – poses a major challenge to the agricultural sustainability needed to build food security (Alexandratos 1995; Lipton 2001).

The United Nations (UN) FAO defines four dimensions of food supplies: availability, stability, access, and utilization. Climate affects availability, since drought and increased average temperatures regularly wipe out crops in developing countries, causing famines. 'Stability' refers to people's risks of temporarily or permanently losing their access to food, through loss of the means to pay for it, for example (Schmidhuber and Tubiello 2007). Stability for the most disadvantaged populations can be directly affected by climate; for example, landless agricultural laborers who depend on agricultural wages in a region of erratic rainfall and have few savings would be at high risk of losing their access to food even though it might be available, if a drought wipes out crops and puts them out of work (Schmidhuber and Tubiello 2007). This same climate effect can also impact indirectly on others, when the subsequent migration of these rural populations to the cities adds to existing competition for incomes (and hence food) among the urban poor (Rao et al. 2011). Food stability among more disadvantaged rural communities can be reduced when climate and the commercial decisions of landowners interact. For example, if the frequency of droughts increases in a rural region of India and landowning farmers decide to switch to cotton or biofuels that require less water to grow, this can have significant impacts on the availability of the cheap staple foods on which impoverished local communities may depend.

'Access' includes access to adequate food for a nutritious diet. Several factors can increase nutritional inequalities by causing shortages of food. These shortages can be avoided by affluent families with the money and the means of transport to secure stocks of food, while disadvantaged communities have little flexibility. 'Utilization' refers to people having enough food but being unable to make use of it, such as if they are chronically ill. This can be further complicated in developing countries where out-of-pocket spending on medicines and health care can have devastating effects on already disadvantaged families, reducing their food budgets even further (Berman et al. 2010). Food insecurity is growing in many countries. Studies suggest that continuing population growth and increasing levels of consumption and demand will result in the world needing at least 50% more food by 2050 (Royal Society of London 2009; Godfray et al. 2010).

> Nevertheless, more than one in seven people today still do not have access to sufficient protein and energy from their diet, and even more suffer from some form of micronutrient malnourishment….the global population will continue to grow, yet it is likely to plateau at some nine billion people by roughly the middle of this century. A major correlate of this deceleration in population growth is increased wealth, and with higher purchasing power comes higher consumption and a greater demand for processed food, meat, dairy and fish, all of which add pressure to the food supply system. (Godfray et al. 2010)

1.07.5 Impacts on Agriculture

Agricultural productivity is not growing fast enough to meet the needs and demands of the world's populations for food, while the numbers of people without enough food are increasing in many countries. Food production will need to continually increase, and to do this more water will be required (Ludi 2009). The water resources of disadvantaged populations are already threatened in many developing countries, and increased droughts increase this threat. Food insecurity and its population health impacts are considered very likely to increase health inequalities between rich and poor nations and between population groups within countries. A global assessment of the potential impact of climate change on world food supply highlighted that any change in local and regional climatic conditions is likely to impose the greatest risk in terms of food security on the poorest countries with economies based heavily on agriculture (Rosenzweig and Parry 1994). In developing countries, farmers' adaptive efforts alone would do little to reduce the disparity between developed and developing countries.

Land suitability is also important. Currently, two-thirds of the world's land is constrained in its suitability for agriculture by being too cold, dry, steep, wet, or infertile. The proportion of land that is unsuitable in regions like southern Africa may also change in the future (Slater et al. 2007). Agriculture is a major part of the economies of many African countries and is often their biggest source of both gross domestic product (GDP) and foreign exchange, which again impact on their ability to feed their populations. Likewise in Mongolia, where livestock provide food and livelihood for very large numbers of people, large areas of land are also under threat of becoming unsuitable for pasture because of the threats of overgrazing and increasing aridity (UNDP 2011; Ministry of Nature & the Environment of Mongolia 2006).

Governments' attempts to protect the food security of their populations may be undermined to some extent by globalization and by the ability of other countries and large corporations to buy their land. Land suitable for agriculture in developing countries is sometimes taken over in large-scale purchases by transnational corporations and oil- or capital-rich but food-poor foreign governments. More than 50 Mha of land in Africa was acquired or negotiated for in this way in 2009 (Lambin and Meyfroid 2011). Food and biofuel grown on this land is usually destined for export, and the use of land in this way may conflict with the food and nutrition needs of some of Africa's more disadvantaged populations.

The impacts of climate on food security are complicated by a number of additional factors, not least the growth of some populations. Food prices are another factor – the World Bank estimated that in the 3 years from 2005, overall world food prices rose by 83% (World Bank 2011). In addition, globalization has resulted in significant interdependence of countries for access to food. The United Kingdom imports 90% of its fruit and about 60% of its vegetables and was therefore at risk of running short of fruit and vegetables in 2010 because of a ban on flights imposed by a volcanic ash cloud over Europe (Wray and Wearden 2010). The situation was illustrative of the potential impacts of extreme weather events on food availability in countries dependent on imported food, as well as on the economy of many developing countries where agriculture remains the largest employment sector and rural livelihoods depend on exporting food (WHO 2012).

Impacts on agriculture, food exports, and livelihoods may be made worse by background policy changes in one continent that can have large impacts in another. For example, an analysis by the World Bank in 2001 estimated that the implementation by the European Union of a new aflatoxin standard would reduce the health risk in Europe by 1.4 deaths per billion people, yet could decrease African exports by 64% (Otsuki et al. 2001). The importance of food safety standards to minimize risks to health is undeniable, but they need to be complemented by policies and actions that enable growers to attain these standards and safeguard their exports. The Overseas Development Institute proposes that unless mitigation policies designed in developed countries on issues such as biofuels and carbon markets consider their potential impacts on trade in developing countries and integrate them with global poverty reduction programs they risk exacerbating the existing restricted access of the poor to food resources (Prowse and Peskett 2008).

1.07.6 Water and Agriculture

Water is a key factor in agriculture, with the impact of climate change in increasing floods (McMichael et al. 2006) and drought being obvious examples (Bates et al. 2008). In Peru, for instance, a large proportion of the population is economically deprived, and the country was assessed as South America's most water stressed – in 2007, about 70% of Peru's population was living in the coastal desert, which held only 2% of the country's water (Rubio 2007). The region is losing large amounts of the glaciers that feed Peru's rivers thereby already facing significant droughts and their consequent impacts on agriculture. Water availability is also dependent on how it is conserved and utilized, on the amount allocated to agriculture by governments, and on how its utilization may be influenced by businesses.

1.07.7 Potential Risk of Temperature and Precipitation Changes on Agriculture: the Example of India

India's economy is highly dependent on agriculture, and a long-term rise in average temperature would affect many crops and hence people's livelihoods and the ability to feed their families. In one possible future scenario, the Indian Agricultural Research Institute projects that an increase in the atmospheric concentration of CO_2 may tend to increase yields of rice, wheat, legumes, and oilseeds. There may be improvements in yields of chickpeas, maize, sorghum, millets, and also (especially in the western parts of the coastal region) coconuts (Aggarwal 2011). However, increases in temperature may decrease yields of wheat, soybean, mustard, groundnut, and potato. Regional climatic changes have also been projected to lead to a possible 3% loss in potato production by 2020, and a possible 14% by 2050, so assuming an impact of 5% loss in production over 2010 figures by 2030 might be conservative. The quality of some crops may also be impacted. Aggarwal (2011) reported that temperatures above a mean of about 27 °C led to increasing decline in the quality of basmati rice (a highly valued rice with a notable fragrance and delicate flavor). This could potentially have an impact on farmers' and India's ability to compete in markets, with consequences for income and occupation and hence for health.

While rain is very important for the successful cultivation of rice and the amount of sunlight also influences rice yield in the last 35–45 days of its ripening period, temperature is the most crucial factor likely to impact on rice growing in India. Average annual temperatures have for decades had a positive influence on the yield of rice (which requires 20–40 °C to grow). Thirty degrees is the optimum in the daytime, and 20 °C at night. Bright sunshine within the lower temperature range during ripening helps the development of carbohydrate in the grain. Thus weather has a crucial role in both the growth and the availability of rice – a principal food crop in India.

Nights have been warmer in India over the past decade (an increase of 0.2 °C), and the FAO reported that during that period, India's rice yields leveled off. It has been established (Peng et al. 2004) that a 1 °C increase in night temperature leads to a 10% reduction in rice yield. When people in India become wealthier, they tend initially to eat more rice, but then as they become better off, their rice intake tends to decline as they eat other foods (Wassman and Dobermann 2007). Nighttime temperature increases have also been shown to decrease wheat yields – the duration of the period in which the grain fills begins to decline at night temperatures of $\geq$20 °C (Prasad et al. 2008). So reductions in rice (especially) and wheat availability, and a rise in the price, could have a large impact on poorer citizens in India, and widen the 'health gap' as their food intake may decline, unlike that of wealthier citizens. This could be a potential health disaster for many across the regions of India.

1.07.8 Inequalities in Food Security

A major public health study (Patz et al. 2005) concluded that the effect of climate change on food crop yield will probably exacerbate regional food supply inequalities. These effects are greatest in poorer populations at low latitudes, which face the most important climate-sensitive health outcomes (malnutrition, diarrhea, and malaria) and where vulnerability to climate effects is greatest (McMichael et al. 2004). Many analyses conclude that within those countries, the most deprived populations will be the hardest hit. One WHO study estimated that the DALY burdens per capita would be several hundred times greater in the poorer regions of Africa, parts of the Eastern Mediterranean region, and Southeast Asia than in Western Europe, North America, and the more developed regions of the Western Pacific (McMichael et al. 2004). The estimated mortality attributable to climate for the year 2000 was 0.15 deaths per million in WHO AMR-A Region (the most developed part of the Americas including Canada, Cuba, and the United States) but 65.79 in SEAR-D (eight countries in Southeast Asia including India, with high child and adult mortalities), 66.83 for AFR-D (a grouping of African countries with high child and high adult mortality), and 109.40 for AFR-E (African countries with high child and very high adult mortality).

1.07.9 Fish Stocks

Fish, crustaceans, and molluscs are very important food sources and are estimated to provide nearly three billion people with 15% or more of their animal protein intake. They can make up 50% of the animal protein supply of some small islands and West African states (Godfray et al. 2010). Seafood trade plays a major role for many deprived populations in developing countries by providing the incomes that enable them to buy enough food. Capture fishing provides just over half of the fish eaten by humans worldwide, while aquaculture contributes the rest (FAO 2010).

Climate-related factors have large impacts on fish stocks, affect the productivity of aquaculture systems, and increase the susceptibility of cultured fish to disease (Jaykus et al. 2008). The FAO's comprehensive analysis (Daw et al. 2009) of the impacts of climate variability show that very complex changes are expected in the world's fish stocks. Any significant increase in temperatures in different parts of the oceans could contribute to large changes in nutrient supply and fish stocks. While temperature is a very important factor, changes in ocean chemistry, including acidification from rising levels of CO_2, may have even more important impacts on animal and plant species (Harley et al. 2006).

Coral reefs play a key role in the aquaculture and fisheries of many islands. Crabbe (2009) stated that since reefs provide an environment in which one-third of marine fish are found and from which 6 million tons of fish were caught annually in 2008, increases in temperatures and continued changes in ocean chemistry may have large negative impacts on fish stocks during the twenty-first century by further damaging the world's coral reefs. Research suggests (Crabbe 2009) that increases in CO_2 levels in seawater may weaken the skeletons of some corals and reduce their ability to withstand erosion and compete for space. Corals bleach when exposed to prolonged above-normal temperatures, and this also can result in decrease in growth and recovery rates. While there is some evidence that corals can adapt, a possible future scenario is that the frequency of bleaching events could increase and become an annual process in most oceans. Agriculture and fisheries in the tropics are often associated with coral reef ecosystems in islands. Some of the poorer and less empowered countries closer to the equator may be more vulnerable, while also finding it harder to adapt. This is likely to be the case for countries depending on fisheries located in deltas or on coral atolls vulnerable to flooding, saline intrusion, or sea level rise. The FAO considered Sub-Saharan African coastal communities and small island states to be at high risk (FAO 2010). Asia was thought to be the continent most sensitive to the threat of changes in local and regional climatic conditions on aquaculture, while Africa and Latin America may have high growth potential for aquaculture, but to reduce risk would need the planning of adaptation and mitigation strategies (Cochrane et al. 2009). However, more than 90% of global animal aquaculture occurs in developing countries, many of them having the weakest institutional capacity to protect and improve ecosystem health (Smith et al. 2010).

Climate influences on fishing and aquaculture are compounded by economic factors impacting on the industries and affecting food security and inequalities. Rising demand among the European Union, Japan, and the United States, coupled with their ability to dominate pricing, may tend to decrease the amount of income and also the fish protein available to the smaller suppliers and the poorer populations in developing countries (FAO 2010). While the impact of price on different countries is complex, there is continuing strong pressure on developing countries to export seafood to wealthier countries, whose populations already tend to have better nutrition, thus increasing nutritional inequality. Developed countries and large private industries also wield a great deal of power over market access and regulation of food standards, and this may increase access and operational difficulties for smaller suppliers especially in poorer countries. There are also major pressures on current and future seafood stocks because of pollution of marine environments, especially in Southeast and East Asia (Nelleman et al. 2008). Around Pakistan's Karachi Coast, for example, marine disposal of untreated sewage and industrial effluent plus oil discharges from shipping have damaged mangrove forests and marine life and will have long-term impacts on fish (Government of Pakistan Environment Agency 2012). Abandoned, lost, and discarded fishing gear is an increasingly significant threat to fish stocks and their environments around the world, while over-harvesting and bottom trawling around the world are degrading fish habitats on a massive scale, with many species now being harvested close to capacity. At the same time,

> Illegal, unreported and unregulated fishing continues to threaten the long-term sustainable management of world fisheries. (FAO 2010)

There are also worldwide problems with fleets discarding unwanted fish on an enormous scale, including the killing and discarding of huge quantities of juveniles of economically valuable species, inevitably leading to species' decline. The pressures on species may be compounded by highly contagious aquatic animal diseases from poorly governed aquaculture, leading to serious losses and long-term damage (Nelleman et al. 2008).

These pressures vary widely between countries and in many developing countries can lead to fish populations being pushed beyond their limits. World Trade Organization rules may not differentiate between well- and poorly managed fisheries and aquaculture, and this can be compounded by poor governance in some developing countries. All these large impacts appear likely to complicate problems of food security for developing countries during a century in which sea warming is displacing fish stocks toward the poles and tending to reduce them in tropical waters (FAO 2010).

1.07.10 Livestock

Livestock productivity has been shown to be sensitive to temperature extremes (Nienaber and Hahn 2007), and farmers have to increase water and shade for their animals if mean temperatures increase. Animal reproduction may be adversely affected by increasing temperature and humidity (Epperson and Zalesky 1995). In Mongolia, where there is clear evidence of warming consistent with climate change (UNDP 2011), extreme weather events, drought, and associated land degradation, as well as overgrazing, have reduced forage yield, livestock production, and hence food availability. Its economy until recently had been almost entirely dependent on herding and agricultural production (M.A.D. Investment Solutions 2012), and severe drought and extreme cold have repeatedly exacted a heavy toll on the national economy. Drier conditions resulting from increased temperatures could increase the area of desert in Mongolia, a country where approximately 70% of the land is already classified as desertified, and reduce pasture by 10–30% (UNDP 2011). In 1999–2000 and 2000–01, the country was struck by two consecutive 'dzud' events, a Mongolia-specific winter disaster, which undermines the welfare and food security of the herding community through large-scale death and debilitation of livestock. Climate conditions in 1999–2000 led to 12 000 people losing all their herds, and in the following winter, 13% of Mongolia's livestock died, resulting in severe impacts on the economy and a GDP growth of 1.1% in 2000 and 1% in 2001 (M.A.D. Investment Solutions 2012). Declining herds are increasing starvation risk and extent among the population. When farmers have very low incomes, lower yields can have major impacts on the nutrition of their families.

1.07.11 International Policy Impacts

Increased global awareness of the entire spectrum of environmental risks is an essential precursor to the introduction of effective policy changes. However, some well-intentioned public responses to greater awareness of the human activities that generate greenhouse gases may have unforeseen negative consequences on other communities. One example is the concern regarding ’food miles,’ which measure how far a food has been transported to the dinner plate (Lang 2009). The concept originally developed to highlight to consumers the hidden environmental costs of food production, has more recently been shown to be misleading (McKie 2008). Food produced in a highly environmentally friendly manner in distant lands may account for less CO_2 emissions than locally produced food grown in an area of high use of fertilizers and mechanized farming. Changes in consumer behavior encouraged by concerns regarding food miles may also have other wider socioeconomic impacts. It has been estimated that stopping the import of fruit and vegetables from African countries would reduce the United Kingdom’s carbon emissions by less than 0.1%, while in 2008 it provided incomes for more than one million people living in rural Africa (Prowse and Peskett 2008) and thus could harm their livelihood if curtailed. Strategies should hence be developed that benefit the most disadvantaged people in developing countries while reducing environmental impacts. Similarly, increasing demand for biofuels as an alternative to petroleum products needs to be met in ways that do not increase food insecurity. If land is given over to biofuel crops on a large scale, they can displace important food crops. They can also drive up crop production costs such as rural labor and fertilizer. If this drives up the price of basic staple crops, the poorest people – often the urban poor – may be the first to suffer. Higher food prices have a direct impact on their ability to buy food (Godfray et al. 2010).

1.07.12 Food Safety

Climate impacts food safety, and long-term warming increases the risks (Jaykus et al. 2008). There are a number of causal pathways through which this occurs. Climate affects agricultural pests and diseases. Increasing ambient temperatures may be a contributing factor to the increased prevalence of insects, bacteria, viruses, and fungi, and hence this can impact on crop yields. Increased flooding can increase or cause chemical contamination of crops and hence foodstuffs (Jaykus et al. 2008). Any rise in average temperatures could also increase hygiene risks in food storage and distribution. Temperature and rainfall data have been used in Australia to predict numbers of cases of salmonellosis (Zhang et al. 2010). Climate affects disease transmission between vertebrate animals and humans by altering vector cycles and animal reservoirs and could conceivably result in new diseases. An increase in sea temperatures would provide more favorable environments for the growth of phytoplankton and for toxic algal blooms, which can accumulate in filter feeders, including the bivalve mollusks used by humans for food. Raised sea temperatures can also promote the uptake of mercury by fish and its accumulation via food chains. This may (Booth and Zeller 2005) lead to continuous increases in concentrations of methyl mercury in the tissues of people from communities with high intakes of fish, such as the Faroese. Raised sea temperatures are suspected of increasing the growth of *Vibrio* spp. (Paz et al. 2007), which are dangerous to humans and can be transmitted via infected fish or from immersion in contaminated water.

1.07.13 Vulnerability and Adaptation

Climate-related factors are likely to have major negative impacts on the ability of developing countries to gain food security for their most disadvantaged populations in the twenty-first century. There are many competing demands for land that could be used for agriculture, such as those from urbanization, and there are now no major new fishing grounds available (Godfray et al. 2010). While action on adaptation and mitigation within developing countries is needed, many countries that are vulnerable to the impact of climate on food security may not have the governance necessary to implement appropriate changes. Developing countries may also find their intentions constrained by the economic, legislative, and trade decisions of wealthier countries. Comprehensive strategies between countries combining agriculture, trade, aid, economic policy, earth sciences, public health, weather forecasting, and scientific advice to growers are needed. Action and strategy (such as those on ‘food miles’ (Lang 2009), for example) must be global, regional, and also local.

1.07.14 Regional Sensitivity

Studies highlight how strategies to address climate-induced impacts on food security must incorporate major factors such as trade, aid, and food prices and hence be modified at national and regional levels. However, they must also be sensitive and specific enough to be useful in mitigation and adaptation for specific geographical and population areas and would need to include demand modeling. In China, analyses suggest that agricultural water demand in the south and cropland soil-moisture deficit would decrease, while rain-fed crops in north and northeast China may face water-related challenges in the coming decades because of expected increased water demand and soil-moisture deficit and a projected decrease in precipitation (Tao et al. 2003). Similarly, there is a great difference in vulnerability to climate effects between individual regions in Peru (Rubio 2007). While the country has many harsh environments and an overall shortage of water, studies show that climate impacts in very different ways in different regions. In one region it resulted in droughts due to the disappearance of glacier melt water, while in another it led to the appearance of a new lake 150 km long in a desert, following El Nino-induced rainfall increases. Thus, to be effective, adaptation would require monitoring and action specific to localized areas with different crops and agriculture. While countries necessarily look to scientific innovation and highly technological agriculture for mitigation, Rubio (2007) points to the potential for a return to traditional locally developed agriculture such as raised fields, artificial swamps, and local crops that had long been adapted to high altitude environments but were displaced by more modern ones.

Mitigation needs to be not only informed by weather monitoring and prediction systems developed to meet farmers’ and growers’ needs but also supported by earth science ministries with intelligence about pests and about which food crops are suited to predicted weather conditions. This would, for example, help growers switch to alternative food crops rather than export crops like cotton, so as to help protect food security in their area.

A World Bank report highlighted that food needs may increase steeply by 2050, when the global population reaches nine billion against a background of reduced global average agricultural yields (World Bank 2012). Impact studies are pointing to severe difficulties particularly in Sub-Saharan Africa and South Asia where rural households are highly dependent on agriculture for their livelihoods and farming systems are highly sensitive to climate. It is recognized that agriculture is the sector most vulnerable to climate and at risk from changes in climatic conditions and is also itself a major cause of climate change, directly accounting for about 14% of greenhouse gas emissions (World Bank 2012) as well as altering the albedo, surface roughness, surface heat, and moisture fluxes due to large areas of land-use change (Marland et al. 2003; Pielke et al. 2011; Avila et al. 2012). Despite this, sustainable agricultural policies and practice can be a part of the solution, enabling people to feed themselves and adapt to changing climate while also contributing to its mitigation.

1.07.15 The Role of Farmers in Adaptation and Mitigation

The effects of climate variations are not new to farmers, but climate change has greatly increased their vulnerability. Farmers can nevertheless play a major role in adaptation and mitigation. ′Triple win′ interventions are possible that can generate higher yields, more carbon in the soil, and greater resilience to droughts and heat, resulting in poverty reduction and greater food security. However, achieving food security globally will require reengineering the complex food ′system′ through the active engagement of governments, science, business, the farming profession, and civil society at local, national, and international levels.

In November 2011, during the run up to the UN climate change talks held in South Africa, the independent ′Commission on Sustainable Agriculture and Climate Change′ (2011) made up of eminent scientists released a ′summary for policy makers,′ which highlighted the following action points:

1. Integrate food security and sustainable agriculture into global and national policies
2. Significantly raise the level of global investment in sustainable agriculture and food systems in the next decade
3. Sustainably intensify agricultural production while reducing greenhouse gas emissions and other negative environmental impacts of agriculture
4. Target populations and sectors that are most vulnerable to climate change and food insecurity
5. Reshape food access and consumption patterns to ensure basic nutritional needs are met and to foster healthy and sustainable eating habits worldwide
6. Reduce loss and waste in food systems, particularly from infrastructure, farming practices, processing, distribution, and household habits
7. Create comprehensive, shared, integrated information systems that encompass human and ecological dimensions

A collective effort to reshape food production access and consumption patterns worldwide is the only route to ensure a food secure planet in the future.

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1.08 Heat-Related Mortality

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1.08.1 Introduction

Weather has been implicated as a causal factor in a wide range of diseases from early history. The first studies were observations of seasonal and geographical patterns in disease. When deaths became routinely reported, seasonal patterns were described in the earliest health statistics. More recently, sophisticated statistical techniques have been developed to quantify the acute effects of meteorological parameters to capture the day to day effects of weather (temperature) on human health. This chapter will describe the current state of knowledge regarding the effects of hot weather (environmental high temperature) on human health. The chapter focuses on impacts in high-income countries in temperate climate zones (Europe and North America).

We are now seeing a resurgence of interest in quantifying the effects of weather and climate on health because several major heat wave events have occurred, and there is increasing concern about anthropogenic climate change at the local, regional, and global levels. One of the impacts of climate change from greenhouse gas emissions is an increase in the future frequency and intensity of heat waves, as assessed by the Intergovernmental Panel on Climate Change (IPCC 2007, 2012).

1.08.1.1 Seasonality and Mortality

There has long been interest in the seasonal patterns of mortality (Alderson 1985). In the early nineteenth century, European countries exhibited peaks in mortality in the summer season. By the 1840s, England was showing winter peaks in mortality, with the exception of the years 1849, 1854, and 1866, when a large excess in summer deaths occurred because of major outbreaks of cholera (Farr 1852). Such changes in the seasonality of mortality in a population over time is also an illustration of the 'environmental risk transition' (Smith 1990). As countries develop economically, they undergo a change in risk patterns from those associated with traditional environmental hazards (lack of adequate water and sanitation and infectious and parasitic diseases) to modern risks (associated with an increase in chronic noncommunicable diseases) (Smith and Ezzati 2006).

A second seasonal mortality pattern has been observed in high-income populations, as modern risks then decline because of public health or other policy measures. Thus, a decline in excess winter mortality since the middle of the past century has been observed in many high-income countries. In the Netherlands, a 50% reduction in excess winter mortality between the 1950s and 1970 was reported (Kunst et al. 1991). Several authors have suggested that this is due to improvements in winter home heating (Sakamoto-Momiyama and Katayama 1971; Keatinge et al. 1989). This has lead to a progressive *deseasonalization* in mortality patterns as countries develop economically.

1.08.1.2 Temperature Regulation and Heat Injury

Healthy adult persons have efficient heat regulatory mechanisms that cope with increases in temperature up to a particular threshold. The body can increase radiant, convective, and evaporative heat loss by vasodilatation (enlargement of blood vessels in the skin) and perspiration. High temperatures cause some well-described clinical syndromes such as heat stroke, heat exhaustion, heat syncope, and heat cramps (Kilbourne 1997). Heat stroke occurs when the core body temperature reaches 40.6 °C and leads to multiple organ dysfunction and death. Heat stroke has a substantial case–mortality ratio, and progression to death can be very rapid (within hours). In survivors, there is an increased risk of long-term sequelae, including permanent damage to organs (Dixit et al. 1997), severe functional impairment (Dematte et al. 1998), and a risk of early mortality (Wallace et al. 2007).

Persons who are physically active in high temperatures are also at risk of heat illness (and exertional heat stroke). Occupational studies have also shown that at high ambient temperatures workers experience reduced cognitive ability and an increased risk of accidents and heat injury (see Occupational Health chapter, Kjellstrom et al., this volume).

When people sweat and do not drink sufficient water, they are at risk of dehydration and decreased urinary concentration. Low urine volume is a known risk factor for lithogenesis (formation of stones) and clinical renal colic (sudden severe pain associated with the passing of stones) (Boscolo-Berto et al. 2008). Although this is an acute effect of high environmental temperatures on health, it is rarely fatal and therefore not an important mechanism for heat-related mortality.

The majority of deaths that are 'attributed' to heat are not from heat stroke. Rather, they are defined retrospectively from the observed temperature–mortality relationship. Many causes of death are sensitive to heat effects. Studies of heat-related mortality in England and Wales (Gasparrini et al. 2012) and the United States (Anderson and Bell 2009) found that respiratory and cardiovascular causes were most sensitive, but nearly all major disease outcome groups show some sensitivity. Heat-attributable deaths are therefore defined statistically at the population level (using observed temperature–mortality functions or calculated as the number of deaths during a heat wave that are above a baseline/expected mortality level).

It is likely that there are several mechanisms by which a person may succumb during (or shortly after) a hot day, as the environmental temperatures places extra strain on a person whose health may already be compromised in some way. All other things being equal, any (chronic or acute) illness that compromises thermoregulation will increase the risk of heat-related death. If the exposure to heat is severe enough, even healthy people will succumb to heat stroke and death. Illnesses also compromise mobility, awareness, and behavior, and it has been shown that dementia and Parkinson's disease also increase the risk of heat-related mortality (Stafoggia et al. 2006). Overall, the epidemiological literature shows that the effect of temperature on mortality at the population level is different from that predicted by physiological processes in individuals. Therefore, epidemiological studies on cause-specific mortality can provide useful insights into the mechanisms by which daily temperature affects mortality.

Deaths certified as due to heat should be deaths from classical or exertional heat stroke, which may or may not be related to the weather (WHO 1977, 2007). Following the Chicago heat wave, attempts were made to improve the certification (reporting) of heat-related deaths (Shen et al. 1998). The US Centers for Disease Control and Prevention (CDC) regularly reports the incidence of heat mortality in United States (CDC 2006); 3442 deaths from exposure to extreme heat were reported during the 14-year period 1999–2003 (annual mean: 688 deaths). In two-thirds, the underlying cause of death was recorded as exposure to excessive heat; for the rest, hyperthermia was reported as a contributing factor. Deaths were higher in men than women in all age groups. The age distribution indicates that rates are highest in those older than 65 years and that deaths in children were relatively rare (228 deaths, 7% of total). The high mortality rate in adults (1810 deaths, 53% of total) probably indicates the importance of occupational exposures (see Occupational Health chapter). The states with the highest average annual hyperthermia-related death rates were Arizona (1.7 deaths per 100 000 population), Nevada (0.8), and Missouri (0.6) (CDC 2006).

1.08.2 Heat Waves and Their Impact on Health

The impact of hot weather becomes most apparent during extreme hot episodes (heat waves). In August 2003, an unprecedented heat wave affected most of central and western Europe. The overall estimate for excess mortality in August was just less than 45 000 deaths (Robine et al. 2008). The impact in France was considerable, with an estimated 15 000 excess mortality in a 20-day period (Hemon and Jougla 2003). A notable impact of the heat wave was the late detection of the mortality and morbidity impacts by the established public health surveillance system. Figure 1 illustrates the mortality peak (short-term increase in daily mortality) associated with the 2003 heat wave in London, United Kingdom. The excess mortality due to this event was estimated to be 616 in London and 2091 in England and Wales (Johnson et al. 2005).

In Europe, countries in southern Europe experience the highest temperatures and are also most sensitive to heat wave effects (Baccini et al. 2008). In Athens, in 1987, a 10-day heat wave resulted in 926 deaths that were classified as heat related. However, the excess mortality was estimated to be more than 2000 (Katsouyanni et al. 1988). In all urban areas in Greece except Athens, a 32.5% increase in mortality was observed in July 1987 compared to the average July mortality during 1981–86 (WHO 1977).

The midwestern region in the United States has also experienced several major heat wave events. The heat wave in Chicago in 1995 caused 514 heat-related deaths 12 per 100 000 population) and was associated with failures in the power and water supply systems as well as institutional failures in the heat wave response (Whitman et al. 1997). All heat wave deaths are considered to be preventable: the 1999 heat wave of similar magnitude caused 114 heat deaths in Chicago (Klinenberg 2002), indicating that 'adaptation' was relatively effective in reduing mortality, but not sufficient to prevent all the excess mortality. The highest sensitivity to heat-related mortality in United States is more in the northern cities.

1.08.3 Methods for Characterizing the Temperature–Health Relationship

Descriptions of seasonal patterns and individual events (episodes) only provide limited information on the causal processes of weather and climate effects on human health. Many nontemperature factors also vary on a seasonal basis. Heat waves are rare events and vary greatly in characteristics and additional

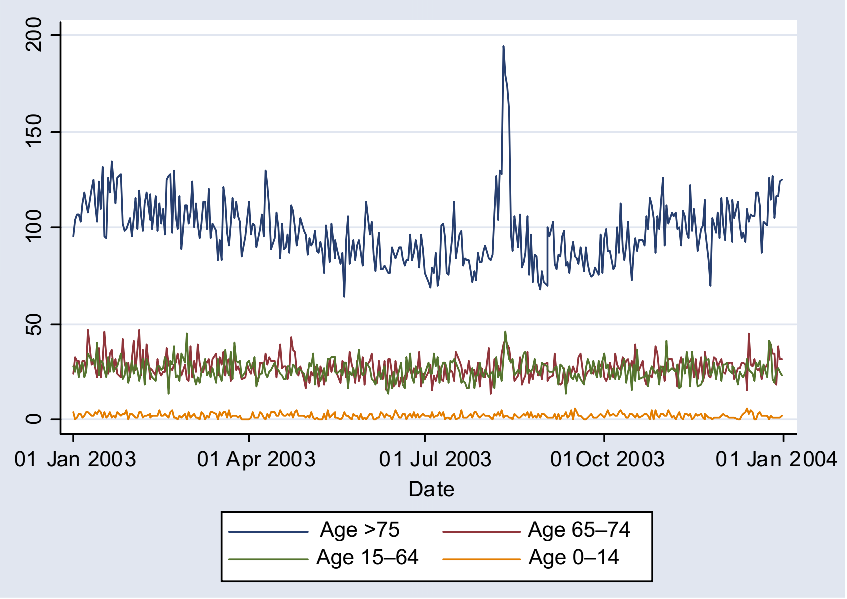

Figure 1 Daily mortality during the 2003 heat wave in London, UK. Source: Data from ONS.

exposures (e.g., air pollutants). A variety of methods have been developed to describe the effects of weather on humans. Early research in Europe focused on the classification of weather types that triggered particular symptoms. Recent developments have focused on quantitative models and increasing parameterization of the thermal environment. Epidemiological studies, however, which require long time series and population-level exposure indicators, have relied on daily data from weather stations that are routinely (but not always freely) available. Time series regression studies of acute effects are seen as the most robust approach to quantify the weather and health relationships (Basu 2009; Armstrong et al. 2011).

Populations in temperate climates show an increase in mortality risk above a population-specific threshold value. Figure 2 illustrates this relationship for London, United Kingdom. The key parameters in these studies are the heat 'threshold' value and the slope (or coefficient) of the change in mortality risk per unit change in meteorological parameter above the threshold value. There is generally less evidence for a threshold for cold effects (Analitis et al. 2008).

The whole population is assumed to be exposed to 'heat' and 'cold.' To date, population-based studies have used outdoor air temperature (or temperature-based indices), usually from a single weather station, as the exposure measures. Individual exposures to temperature are likely to relate more closely to indoor temperatures because people (at least in high-income countries) spend majority of their time indoors. However, this will depend on the population and climate. There are few studies that link indoor temperatures with health outcome risk, and these have mostly addressed cold exposures. Indoor temperatures are determined by housing characteristics and behavior as well as the outdoor temperatures. In addition, urban areas are often warmer than surrounding areas (i.e., have higher outdoor temperature) because of the urban heat island effect (see below).

Epidemiologists have generally preferred to use simple meteorological variables in their analyses, such as temperature, as the main exposure variable. Other meteorological variables can be included as confounders (humidity, barometric pressure, and wind speed). However, this is not straightforward because the meteorological variables are not independent. Therefore, some studies used indices that combine temperature with humidity, for example, apparent temperature (Steadman 1984).

The mortality attributable to a heat wave event is often estimated using episode analyses. That is, the attributable or 'excess' mortality can be estimated by subtracting the 'expected' mortality from the observed mortality. The expected mortality is calculated using a variety of measures, including moving averages and averages from similar time periods in previous years. Estimates are therefore sensitive to the method used to estimate the 'expected' mortality. Published studies have used different methods, and this makes comparison difficult.

A proportion of the 'acute' effect on mortality of heat waves may be due to the hastening of death in already ill persons by a few days or weeks. The mortality displacement effect can sometimes be seen in the lower-than-expected mortality immediately following a heat wave. The key question is, "What proportion of deaths was brought forward by more than a matter of days/weeks?" Several methods have been suggested for estimating the contribution of mortality displacement in daily time series models (Hajat et al. 2005). The extent of mortality displacement due to extreme temperatures has yet to be resolved.

1.08.4 Determinants of Vulnerability to Heat-Related Mortality

There are important differences in the temperature–mortality relationships between populations that cannot be explained by climate alone. The identification of these modifying factors is

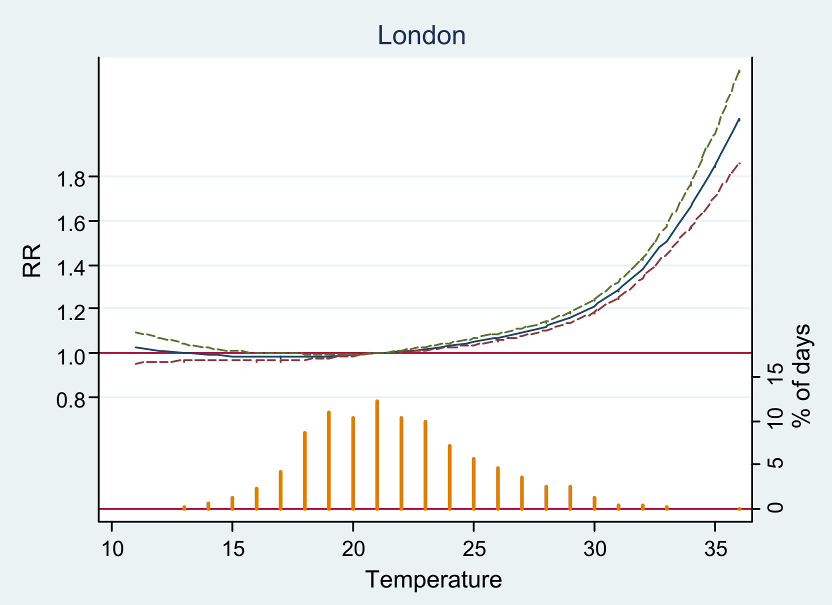

Figure 2 Temperature–mortality relationship in London. Source: Armstrong, LSHTM, Annu. Rev. Public Health 2008. 29: 9.1–9.15

an important research question, and it also enables 'heat wave' interventions to be targeted appropriately at high-risk groups (Figure 3). Most of the current information comes from time series studies and more recently, from case-crossover studies, which have been shown to provide comparable results (Basu et al. 2005).

1.08.4.1 Age and Aging

The 'natural' patterns of aging (senescence) are associated with impairment of thermoregulation (Drinkwater and Horvath 1979) including reduced thermal perception (Collins et al. 1981). Some common medications are known to interfere with thermoregulation. At the population level, several studies provide strong evidence that age is a risk factor for heat- and cold-related mortality (Gasparrini et al. 2011; Hajat et al. 2007; Åström et al. 2011). Studies, however, vary at the age at which the vulnerability is shown to increase. Most population-based time series studies show an effect in adult age groups, but the effect is larger in those older than 75 years compared to other ages. Furthermore, it can be argued that chronological age is a poor indicator of risk, as it is really disability and cardiovascular fitness that are the main determinants of susceptibility to environmental heat.

Infants do not have well-developed thermoregulation and are sensitive to high temperatures. However, mortality due to heat in this age group is extremely low.

1.08.4.2 Gender

Overall, studies indicate that there is no difference in susceptibility to heat-related mortality between men and women (Alberdi et al. 1998). The evidence for heat-related mortality risk being greater in woman in high-income countries is

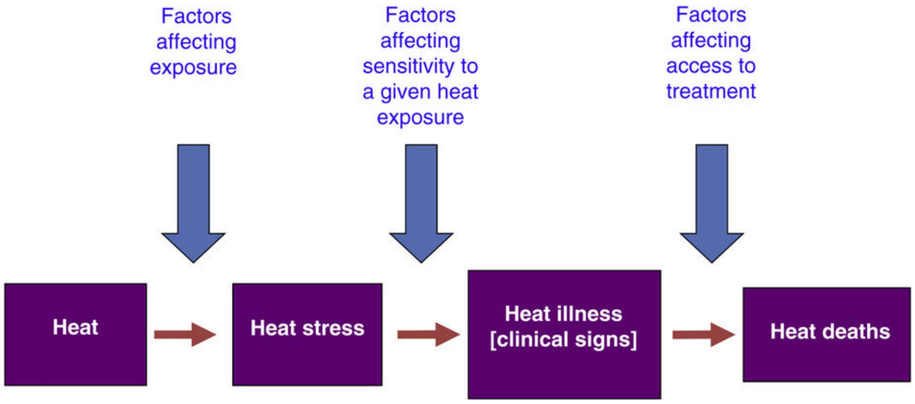
Factors affecting exposure
Factors affecting sensitivity to a given heat exposure
Factors affecting access to treatment
Heat
Heat stress
Heat illness [clinical signs]
Heat deaths

Figure 3 Factors determining the risk of heat-related mortality. Source: WHO 200x, Armstrong, B., and Coauthors, 2011: The association of mortality with high temperatures in a temperate climate: England and Wales. *J. Epidemiol. Commun. Health*, **65** (4), 340–345.

generally weak and inconsistent. However, because there are more women than men in the older age groups (because women live longer), the burden of heat-related mortality in women is greater than that in men. From a physiological point of view, women may be less heat tolerant than men, as they have, in general, higher core temperatures, skin temperature, heart rates, blood pressures, and set points for sweating than men (Havenith 1999). At the population level, such factors may not be important relative to age distributions, cardiovascular fitness, and other factors. It is possible that social and physiological factors are important in determining risk, and the social factors are likely to be very context specific. For example, in the 1995 heat wave in Chicago, men were at much greater risk of heat death than women (Whitman et al. 1997), and this was attributed to high rates of social isolation among men with low socioeconomic status (Klinenberg 2002).

1.08.4.3 Income and Deprivation

The results from studies in high-income countries in Europe have indicated that deprivation is not a major determinant of heat-related mortality (Stafoggia et al. 2006; Hajat et al. 2007; Kovats and Hajat 2008; Borrell et al. 2006; Ishigami et al. 2008). However, one study in Italy reported a higher risk in low-income groups (Michelozzi et al. 2005), but this study did not adjust for age or other confounders. Studies in the United States have been able to use a multicity dataset of daily mortality in order to get a more accurate description of individual-level determinants of heat risk. Mortality risks associated with extreme heat were greater in the black population, which is used a marker of socioeconomic status (Medina-Ramon et al. 2006). Individuals on low incomes are more likely to have a chronic disease or other medical risk factors, such as cardiovascular disease, and different types of housing, which will all modify the risk of heat-related mortality. It is therefore difficult to separate out the determinants of risk within this population, particularly where there is a lack of individual-level data on important risk determinants.

1.08.4.4 Housing Characteristics and Air-Conditioning

People spend a significant amount of time indoors, and so indoor temperatures are likely to play an important role in individual heat exposures, especially for the elderly and children. There is relatively little evidence for the types of housing (and thermal behavior) that increase vulnerability to heat-related mortality. Brick houses (with a high thermal mass), top floor apartments with no through ventilation, and closed windows have all been associated with an increased risk of mortality during a heat wave event (Mirchandani et al. 1996; Vandentorren et al. 2006). Informal housing is likely to be less thermally efficient.

Air-conditioning or comfort cooling has a direct role in reducing temperature exposures in individuals when they are in the cooled environment. There is good evidence that widespread use of air-conditioning in homes and care homes has reduced the mortality burden of heat waves in United States (Dixit et al. 1997; Marmor 1978; Kilbourne et al. 1982; Jones et al. 1982). The lack of air-conditioning may also be one of the reasons why there is more of an income gradient in heat-related mortality risk in United States than in Europe (O'Neill et al. 2005). A recent study found that the presence of air-conditioning reduced the risk of heat-related hospital admissions in California by up to 50% (Ostro et al. 2010).

The role of air-conditioning in reducing temperature-related mortality in populations outside United States remains unclear. It has also been suggested that widespread use of air-conditioning may reduce physiological acclimatization and therefore make people more susceptible to heat waves (O'Neill 2003). A high level of air-conditioning use also increases the risk of power failures during heat waves, which may exacerbate impacts on health.

Several studies in Europe have shown an increased risk in mortality for persons in residential care and nursing homes. The heat wave in 2003 caused a severe impact on elderly persons in hospital and residential homes in France. The mortality rate doubled in the those older than 75 years for persons living in *maison de'retrait* (Fouillet et al. 2006). In 2003, such institutions in France, Italy, and the United Kingdom were often without air-conditioning. A study in United Kingdom also found a much higher 'heat' risk in patients in nursing home and care home, with lowest risk in persons living at home (Hajat et al. 2007). The residents of institutions therefore represent an important high-risk group for heat wave interventions.

There is some evidence of the modification of risk by age group and by health status (frailty). In general, the risk of heat-related mortality increases with the level of disability, in the nursing home setting (Belmin et al. 2007). However, a study in France found the highest risk of heat-related mortality in the less frail patients. The authors suggested that medical care during the heat wave was directed toward 'the most vulnerable patients' and therefore, the risk was reduced in the most vulnerable group (Holstein et al. 2005).

1.08.4.5 Urban Factors

Studies from high-income countries indicate that urban populations are more sensitive than rural populations to heat-related mortality. This is assumed to be because urban populations experience higher outdoor temperatures caused by the urban heat island effect, but other factors relating to population susceptibility may also be important (Oke et al. 1997).

The relationship between cities and weather is complex. The urban heat island effect is caused by day time heat being retained by the fabric of the buildings and by a reduction in cooling vegetation. In temperate latitudes, this has the effect of raising night time temperatures by 1–5 °C (Oke 1995, 1973). Urban heat islands are measured as the difference in temperature between inside the city and the surrounding areas. The magnitude of the urban heat island is, in general, proportional to the size of the city. Urban heat islands are a factor in many cities but tend to be more severe in winter than in summer. Heat islands are dynamic in time and space and are therefore difficult to quantify either spatially or temporally for individual heat wave events. Although much is known about the factors of the built environment that increase temperatures, when estimating health effects within a city, confounding by housing type and socioeconomic factors becomes very important. Thus, few studies have demonstrated within-city effects of heat islands on heat-related mortality risk (Laaidi et al. 2012).

Future urbanization, including the increased use of air-conditioning, will increase the outdoor heat load in cities (Oke et al. 1997; Brazel et al. 2007). The relative impacts of these local, regional, and global anthropogenic changes, including warming from greenhouse gas and cooling from sulfates and other aerosols, are an emerging area of research (IPCC 2007; NRC 2005). One global model study estimated that warming due to urbanization and increased energy consumption was of comparable magnitude to the impact of doubled CO_2 in some regions (McCarthy et al. 2010).

1.08.4.6 Population-Specific Factors

There are now sufficient studies of heat-related mortality in separate locations in order to investigate the causes of the heterogeneity in observed heat effects between populations. There is good evidence that the heat threshold is related to the local climate, and this reflects the acclimatization of the population. A study of 11 cities in United States found that level of air-conditioning was inversely related to the heat slopes (Curriero et al. 2002). An analysis of the heat slopes in the Isotherm study found no significant association with a range of variables, including latitude, gross national product, mean annual temperature, or proportion of elderly (McMichael et al. 2008). A meta-regression analysis of heat slopes in 64 locations, adjusted for the heat threshold, found that increasing population density, decreasing total GDP of city, and increasing the percentage of people aged 65 years or more were all independently associated with an increase in the heat slope (Hajat and Kosatsky 2009). Thus, population characteristics (such as age profile and income) are likely to be important determinants of heat-related mortality.

1.08.4.7 Heat, Violence, Suicide, and Accidents

There are very few daily time series studies of the association between ambient temperature and mortality/morbidity from injuries (intentional or unintentional). In United Kingdom, injuries (e.g., falls) increase in cold and icy weather in the elderly (Levy and et al. 1998). A study of temperature-related mortality in England and Wales found that high temperatures increased the risk of mortality from injuries in adults and the elderly (Hajat et al. 2007). Injuries in children increase in the summer, as they are more likely to be playing outside (Christoffel 1985; Masterson et al. 1993).

Regarding intentional injuries, there is less robust evidence for temperature effects. One time series study found an effect of high temperatures on suicide mortality (particularly by violent methods) in England and Wales (Page et al. 2007). A study in Taiwan also found an effect of high temperatures on violent suicide (but no effect on nonviolent suicides) (Lin et al. 2008). However, the mechanisms were not really clear and countries often have different seasonal patterns in suicide mortality. Evidence for high temperature effects on violence is disputed by psychologists (Rotton and Cohn 2000). Epidemiological studies show inconsistent results, and overall, the evidence is not convincing. A study in Adelaide, Australia, found an increase in ambulance callouts for assault in adults on heat wave days compared to nonheat wave days (Nitschke et al. 2008). However, a study of accident and emergency visits for assault in Cardiff, UK, found no significant correlation with weather factors (temperature, rainfall, and sunlight hours) (Sivarajasingam et al. 2004).

1.08.4.8 Air Pollution and Heat Effects

Simultaneous exposure to air pollutants and both high and low temperatures occur when atmospheric processes that occur in the lower atmosphere are unable to disperse rapidly enough the air pollutants that enter the air space above an urban area. High pollutant concentrations are associated with stable atmospheric conditions in both winter and summer (slow moving or static high pressure areas – anticyclonic conditions). Higher summer temperatures (and ultraviolet radiation) accelerate the formation (and destruction) of the photochemical air pollutants, such as ozone and nitrogen oxide. Thus, ground-level concentrations of ozone are determined by complex atmospheric chemistry driven by ultraviolet light, temperature, and the presence of other pollutants.

Few studies have successfully differentiated weather-induced and pollution-induced daily mortality. In studies of heat-related mortality, air pollutant exposure is a *confounder* because it is associated with both daily variations in temperature (exposure) and daily variations in mortality (outcome). However, air pollutant exposure is also a probable *interactor*. There is only limited evidence of a physiological synergistic effect between temperature and pollutants (Katsouyanni et al. 1993). A recent review found that of the 12 US studies that studied the role of pollutants in temperature–mortality associations there was little evidence of pollution acting as a confounder or effect modifier (Basu 2009). Some studies have found evidence for confounding and interaction between temperature and ozone effects in United States (Ren et al. 2008) and in France during the 2003 heat wave (Filleul et al. 2006).

1.08.5 Risk Assessment for Current and Future Burdens of Heat-Related Mortality

Future populations are likely to be exposed to increasing outdoor temperatures. The implications to human health from such changes have been evaluated primarily in the context of climate scenarios from greenhouse gas forcings (IPCC 2012). Other aspects of climate change (e.g., heat islands) are less well studied. Many factors have a substantial influence on the burden of mortality and morbidity attributable to the 'direct' effects of temperature, which can be considered determinants of population vulnerability and adaptive processes. In epidemiological terms, such factors are effect modifiers of the temperature–mortality relationship.

Health impact assessments of climate change (due to greenhouse gas emissions) have been undertaken at city, national, regional, and global levels. Most future climate impacts assessments use a scenario-driven approach to take into account the uncertainty about future climate and the future world in which those climates will be experienced. Scenarios are plausible and often simplified description of how the future may develop, based on a coherent and internally consistent set of assumptions about driving forces and key relationships. Climate scenarios are generally derived from the output of global or regional climate models. Sometimes the model output is downscaled to local areas (such as cities), but it is not clear if this reduces the uncertainty in the future projection.

As nearly all aspects of our natural, physical, and social environment will change in the future, it is important that these changes are reflected in the scenarios used in climate impacts studies. In practice, however, only population growth and economic growth (in GDP per capita) have been quantified and routinely included in climate impact studies. Several studies have now been published that estimate future heat-related mortality under a range of climate scenarios (to estimate a set of plausible future changes in local temperature exposures) (Huang et al. 2011). Some (but not all) use population scenarios to estimate the future total population and/or the proportion of people belonging to older age groups, who are much more susceptible to heat-related mortality. A common limitation of these studies is that they must make assumptions about how future populations will respond to exposure to high temperatures, including the rate of acclimatization. The studies so far have focused on cities in high income populations and show that heat-related mortality is likely to increase, even when some acclimatization is assumed (Huang et al. 2011; Kinney et al. 2008).

Populations in Europe and North America are aging. In addition, the number of persons with chronic diseases is anticipated to increase. High-income populations are expected to experience a high burden of disease from both cardiovascular and other chronic diseases such as diabetes in the next few decades. These trends are likely to increase the susceptibility to heat (Table 1) (O'Neill and Ebi 2009). In contrast, populations may become less sensitive to temperature extremes due to improvements in the underlying health of the population and improvements in the infrastructure, particularly the uptake of air-conditioning or passive cooling systems to reduce indoor temperatures.

Table 1 Risk of heat-related mortality associated with chronic disease category

Chronic disease category	*Risk of heat-related death*
All respiratory	?
COPD	+
Asthma	+
Neurological damage, Parkinson's disease, etc.	+++
Schizophrenia, psychotic illnesses	++
Dementia, Alzheimer's disease	+++
Diabetes, renal disease	+++
Previous stroke	++
Obesity	+ (elderly) ++ (adults)
Ischemic heart disease	++

+, small risk
++, moderate risk
+++, high risk

1.08.6 Implications for Public Health and Environmental Policy

The impacts on policy and the implementation of specific heat wave public health measures have undergone significant changes in the past decade. Since the 2003 event, most countries in western Europe have implemented some specific public health measures for heat waves, mostly in the form of a heat health warning system. Lessons learned following the event included the lack of an intervention plan for heat waves and the lack of coordination between the social services and health agencies. In addition, very few care homes (*maison de'retrait*) had air-conditioning or other space cooling, and these buildings simply became too hot. The relatively rapid development of these systems can be seen as the success of public health. However, there is still very limited evidence on the most effective ways to prevent heat-related mortality, particularly in community settings (Hajat et al. 2010).

Heat health warning systems use meteorological forecasts to reduce the impact of heat waves on human health and have developed a range of indices to trigger warnings and other actions (Hajat et al. 2009). Epidemiological analyses are required to identify the temperatures at which weather conditions become sufficiently hazardous to human health in a given population to warrant intervention. In practice, this threshold should relate to both the population sensitivity and to operational factors (e.g., is the system designed to protect against only extreme heat events or can it be triggered each year?). Warnings issued to the general public during heat waves reinforce the health messages about heat avoidance behavior. A review of heat health protection messages found that these messages vary between systems (Hajat et al. 2010). Furthermore, the evidence base from some advice is not very clear, such as advice about the use of fans and intake of fluids or salt.

Some cities (e.g., Rome) have an active component of the heat warning systems that include health professionals identifying and contacting high-risk individuals. Heat effects are quite broadly distributed in the population and identifying such individuals is very difficult. Potentially, a very large numbers of individuals need to be contacted. A recent review of current heat avoidance interventions confirmed the importance of valid information on individual risk factors (Hajat et al. 2009). Another limitation of heat warning systems is the recognition that heat-related mortality is not confined to recognized 'heat wave' days (Hajat et al. 2006).

Populations would benefit from heat-related public health actions, which would also need to be targeted at protecting children. However, it is not clear what the best methods for intervention might be. It may be that long-term interventions targeted at improving living conditions would be the most beneficial and cost-effective measures. Without more specific information on the population subgroups most vulnerable to heat-related mortality, it is difficult to make specific recommendations for public health interventions. It is clear that heat intervention plans should be best suited for local needs, through coordination between the local public health agencies, social services, voluntary agencies, and the national weather service.

Another approach to reducing heat-related mortality has focused on the built environment and mitigating the urban heat island effect. Within a given city, the hottest areas are those with the tallest buildings, with the greatest density of buildings, and without green spaces. Therefore, measures to reduce the urban heat islands have focused on the following measures:

- Increasing green spaces and planting trees in streets (trees not only provide shade but also improve air quality)
- Increasing ventilation and air flow (which also improves air quality)
- Increasing the albedo of a city (e.g., painting roofs white)
- Decreasing anthropogenic heat production (e.g., reducing energy-intensive air-conditioning and enhancing natural space cooling of buildings).

The urban heat island is an inevitable consequence of urban development and is an issue for rapidly expanding cities in low- and middle-income countries (Rydin et al. 2012). Appropriate and climate-friendly urban planning, however, may help reduce the magnitude of the urban heat island, but urban planning is often weak in this context. Overall, the benefits of some interventions (e.g., tree planting and increasing albedo) in reducing outdoor temperatures have been shown in some settings. Other benefits (in terms of economic benefits, amenity value, and welfare) of these measures are also apparent. For example, the benefits of tree planting projects include shading, cooling due to evapotranspiration, dust control, runoff control, consumption of carbon dioxide, and water conservation.

1.08.7 Conclusions

The ability to live in different climates around the world is seen as a triumph of human ingenuity and adaptability. Changes in housing, clothing, and behavior allow humans to adapt to climates ranging from the tropics to polar regions; however, even with adaptation, there is a current burden from high-temperature events in terms of premature death, heat injuries, and other health effects. More research is needed to describe the determinants of vulnerability to heat-related mortality and to design interventions that will reduce current and future impacts on health. Such interventions should be cost effective and have environmental benefits, particularly with respect to energy efficiency (Wilkinson et al. 2007). The challenge is to create and maintain healthy cities and healthy houses that protect against both heat and cold and other environmental hazards (Rydin et al. 2012).

See also: Occupational Health and Safety Impacts of Climate Conditions; Cold-Related Mortality and Morbidity.

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WHO EURO

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1.09 Climate, Urban Air Pollution, and Respiratory Allergy

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1.09.1 Introduction

Overall, up to 40% of the general population has been reported to suffer from hay fever (Bousquet et al. 2008) with 23–30% of the population being affected in Europe (Bauchau and Durham 2004). Moreover, the prevalence of allergic rhinitis has increased markedly over the past decade worldwide (Katelaris et al. 2011). Up to 37% of teenagers are affected by asthma symptoms, making it the most common chronic diseases in childhood (ISAAC 1998). Absence from school and limitations in activities are some of the common consequences of asthma. In 2004, the estimated cost of asthma symptoms among children in the European Union was €3000 million, indicating that asthma in children is a substantial disease burden for society (van den Akker-van Marle et al. 2005). Adult asthma is also very frequent, with 15% of adults suffering from this condition. Asthma prevalence varies worldwide (Asher et al. 2006).

For the past 40 years, the prevalence of asthma has in general increased and is still increasing worldwide in parallel with other indices of allergy (Law et al. 2005). However, the falls in some indices of asthma in children in some Western countries with the prevalence of the disease was high, suggesting that the increase may be coming to an end. The leveling-off could be explained by the fact that in such countries all susceptible individuals have become allergic (von Hertzen and Morais-Almeida 2005). In addition, effective asthma therapy has decreased asthma consultation rates and thus the prevalence rates. Asthma is still increasing in developing countries (Asher et al. 2006).

1.09.2 Pollen and Allergic Respiratory Diseases

Pollen grains, which are a causative agent of allergic respiratory responses in patients with pollen allergy, are amongst the commonest allergens, and pollen allergy, because of its elevated prevalence and associated costs, is now a public health problem (D'Amato et al. 2007). In the European Community countries, between 8 and 35% of young adults show IgE serum antibodies to grass pollen allergens, which are the most commonly encountered (Burney et al. 1997) and the cost of pollen allergy in terms of impaired work fitness, sick leave, consulting physicians and drugs, is very high (Pawankar et al.).

Both grass and birch pollen are among main causes of exacerbation and development of rhinitis. Grass pollen counts aggravate seasonal allergic rhinitis in terms of symptoms in a French nationwide sample (a rise of 60 grass pollen grains per cubic meter increased the risk of suffering from a severe seasonal allergic rhinitis by 8% after adjusting for potential confounders and air pollution levels (Annesi-Maesano et al. in press)). Results were also confirmed in the subsample of individuals with documented sensitization to grass pollen. In addition, exposure of the mother during pregnancy to high levels of birch pollen resulted in a tendency toward increased risk of sensitization to the same allergen and symptoms of atopic disease in children with atopic heredity (Kihlström et al. 2003).

So far, the risk of pollen has been scarcely quantified at the population level in the case of asthma. We observed a significant short-term, i.e., within a week, association between grass (Poaceae) pollen counts and consultations for asthma attacks as seen by general practitioners. Adjusted relative risk for Poaceae was 1.54 (95% CI: 1.33–1.79) with an inter-quartile range increase of 17.6 grains/m^3 during the pollen season (Huynh et al. 2010).

The genus *Ambrosia*, which includes both *Ambrosia artemisiifolia* (short or common ragweed) and *Ambrosia trifida* (giant ragweed), has long been recognized as a significant cause of allergic rhinitis. A large random skin test survey demonstrated that 10% of the US population was ragweed sensitive (Gergen et al. 1987). Moreover, Ambrosia pollen levels were significantly related to asthma and rhinitis in a study based on a symptoms diary and peak expiratory flow rates (Newhouse and Levetin 2004). In Europe, ragweed sensitization is increasing, together with the invasion of this weed, especially in central and eastern areas, where it is now presenting a public health issue (Tosi et al. 2011).

1.09.3 Air Pollution and Allergic Respiratory Diseases

Despite some differences in the air pollution profile and decreasing trends of some key air pollutants, namely, industrial toxicants, air quality is an important concern for public health in cities throughout the world.

The most abundant components of air pollution in urban areas are nitrogen dioxide, ozone, and particulate matter (PM). Sulfur dioxide is particularly abundant in industrial areas. It is estimated that more than 50% of the population of the United States lives in areas where levels of ozone, nitrogen dioxide, sulfur dioxide, and particulates exceed current National Ambient Quality Standards, as monitored by the US Environmental Protection Agency (Dockery et al. 1993; Dockery and Stone 2007) With its particulate and gaseous emissions, road traffic is the main contributor to air pollution in most urban areas (Laumbach and Kipen 2012). Although associations between air pollution and respiratory diseases are complex, recent epidemiological studies have led to an increased recognition of the emerging importance of traffic-related air pollution in both developed and less-developed countries (Laumbach and Kipen 2012). A number of experimental and epidemiological studies confirmed the negative effect of urban air pollution on human health and on allergic respiratory diseases (D'Amato et al. 2010), and climate may impact these effects (D'Amato and Cecchi 2008).

1.09.3.1 Nitrogen Dioxide (NO_2)

Car and truck exhausts, together with power plants, are the most significant sources of outdoor NO_2 (EPA), which is a precursor of photochemical smog found in outdoor air in urban and industrial regions and, in conjunction with sunlight and hydrocarbons, results in the production of ozone. Like ozone, NO_2 is an oxidant pollutant, although it is less chemically reactive. NO_2 exposure is associated with increased emergency room visits, wheezing, and medication use among children with asthma (Lipsett et al. 1997; Gauderman et al. 2005). Controlled exposure studies of asthmatics have found that NO_2 can enhance the allergic response to inhaled allergens. NO_2 concentrations in ambient air are also reportedly associated with cough, wheezing, and shortness of breath in children (Rosenlund et al. 2009). In the Swiss SAPALDIA study, long-term exposure to outdoor residential NO_2 was associated with a decrease in lung function and a lifetime history of doctor-diagnosed asthma in adults (Ackermann-Liebrich et al. 1997). A Japanese cohort study also reported an association between NO_2 levels and asthma incidence (Shima et al. 2002). In contrast, a Norwegian study found no association between-modeled NO_2 exposure at the birth address and doctor-diagnosed asthma in a large cohort of children (Oftedal et al. 2009).

A large epidemiological study on more than 18 000 young adults suggests that exposure to high temperature and outdoor NO_2 increases the risk for allergic rhinitis (de Marco et al. 2002).

1.09.3.2 Ozone (O_3)

Ozone is generated at ground level by photochemical reactions involving nitrogen dioxide, hydrocarbons, and ultraviolet (UV) radiation. Ozone inhalation induces epithelial damage and consequent inflammatory responses in the upper and lower airways, as shown by an increase in the levels of inflammatory cells and mediators in nasal and bronchoalveolar lavage (Peden et al. 1995; Lin et al. 2008).

The acute health effects of exposure to ambient ozone have been examined in many geographical regions (Ebi et al. 2008). Potential adverse effects include decrease in lung function, airway inflammation, symptoms of asthma, increases in hospitalization due to respiratory diseases, and excess mortality (Bernstein et al. 2004). Ozone exposure has both a priming effect on allergen-induced responses and an intrinsic inflammatory action in the airways of allergic asthmatics (de Marco et al. 2002; Peden et al. 1995; Lin et al. 2008; McConnell et al. 2002).

In the long term, continuous exposure to high ozone levels impairs respiratory function (Mudway and Kelly 2000) and causes or exacerbates airway inflammation in healthy subjects (Schelegle et al. 2009) or atopic asthmatics, respectively. At the population level, long-term exposure to ozone may reduce lung function in school children and adults and increase the prevalence of asthma and asthmatic symptoms (Peden et al. 1995; Lin et al. 2008; Jorres et al. 1996). In addition, studies have long shown that asthma can be exacerbated by ozone, as measured by increased visits to emergency departments on days with higher levels of ozone and other pollutants (D'Amato et al. 2005; McCreanor et al. 2007). Moreover, an increased asthma prevalence has been observed in milder climatic areas, possibly due to the positive effect of air temperature on ozone synthesis (D'Amato and Cecchi, 2008; Shea et al. 2008).

1.09.3.3 Traffic-Related Air Pollution, Particulate Matter, and Diesel Exhaust Particles

There is evidence that living near high-traffic roads is associated with impaired respiratory health including asthma (Gauderman et al. 2005; Horak et al. 2002; Gauderman et al. 2007). First, McConnell et al. (2002) observed that the incidence of new diagnoses of asthma in children is associated with physical exercise in areas with high concentrations of ozone and PM. Since then, other prospective cohort studies have indicated that long-term exposure to traffic pollution could contribute to the development of asthma-like symptoms and allergic sensitization in children (Laumbach and Kipen 2012). All surveys reported associations with at least some of the studied respiratory symptoms including asthma. Potential long-term effects of traffic exhaust on the development of allergies sensitization were only assessed in the four European birth cohorts (Bråbäck and Forsberg 2009). Long-term exposure to outdoor air pollutants had no association with sensitization in 10-year-old school children in Norway (Oftedal et al. 2007). In contrast, German, Dutch, and Swedish preschool children had an increased risk of sensitization related to traffic exhaust despite fairly similar levels of outdoor air pollution as in Norway (Morgenstern et al. 2007; Brauer et al. 2007). Traffic-related effects on sensitization could be restricted to individuals with a specific genetic polymorphism. Assessment of gene–environment interactions on sensitization has so far only been carried out in a subgroup of the Swedish birth cohort (Melén et al. 2008). These studies, however, are flawed by the fact that no objective assessment of air pollution concentration was available. Individual exposure was estimated by the distance from the highways.

PM is a mixture of organic and inorganic solid and liquid particles of different origins, size, and composition (Ristovski et al. 2012). It is a major component of urban air pollution and has the greatest effect on health. Penetration of the tracheobronchial area is related to particle size and the efficiency of airway defense mechanisms. Ultrafine particulate matter (UFP), with diameters of 0.1 μm or less, is a major component of emissions from vehicles. These particles accumulate into larger fine PM with a diameter $\leq$2.5 mm ($PM_{2.5}$) within short distances from the point of release (Laumbach and Kipen 2012). PM_{10} (particulate matter with a diameter $\leq$10 mm) consists of $PM_{2.5}$ and larger particles of mainly crustal or biological origin, including many aeroallergens. On the basis of epidemiological and laboratory studies, $PM_{2.5}$ appears to be more potent toward respiratory and cardiovascular diseases compared with PM_{10} (Gauderman et al. 2007). PM_{10} can penetrate the lower airways, and $PM_{2.5}$ is thought to constitute a notable health risk since it can be inhaled more deeply into the lungs at the alveolar level (Oberdörster et al. 2005). Human lung parenchyma retains $PM_{2.5}$, whereas particles larger than 5 μm and smaller than 10 μm only reach the proximal airways, where they are eliminated by mucociliary clearance if the airway mucosa is intact (Peden 2008).

A large portion of urban PM originates from diesel engines, the source of diesel exhaust particles (DEPs), which includes other components such as polycyclic aromatic hydrocarbons (PAH). DEPs account for up to 90% of airborne PM in the world's largest cities (Shah et al. 2004; Rield and Diaz-Sanchez 2005) and are composed of fine (2.5–0.1 μm) and ultrafine (0.1 μm) particles, which can also coalesce to form aggregates of varying sizes. Although there were slight reductions in PM_{10} concentrations in Europe in the period 1999–2009, 20% of the urban population still lived in areas where the EU air quality 24-h limit value for PM (PM_{10}) exceeded that in 2009 (EEA 2011).

PM_{10} levels have been associated with early asthma exacerbations in children with persistent disease and with higher prevalence rates even after having considered the dispersion of the particles (Pénard-Morand et al. 2010). Although there is extensive evidence that ambient air pollution exacerbates existing asthma, the link with the development of asthma is less well established, as few studies provide extensive exposure data. In the past few years, birth cohort studies from Germany, Holland, and Sweden, which followed children during childhood, have suggested a positive relationship between PM and physician-diagnosed asthma (Brauer et al. 2007; Gilmour et al. 2006; Morgenstern et al. 2008; Nordling et al. 2008). Researches have elucidated the mechanisms whereby fine particles induce adverse effects; they appear to affect the balance between antioxidant pathways and airway inflammation. Gene polymorphisms involved in antioxidant pathways can modify responses to air pollution exposure (Sacks et al. 2011). Acute exposure to diesel exhaust causes specific effects, such as irritation of nose and eyes, headache, lung function abnormalities, fatigue, and nausea in acute exposure, whereas chronic exposure is associated with cough, sputum production, and diminished lung function (Rield and Diaz-Sanchez 2005).

Studies have demonstrated inflammation in the airways of healthy individuals after exposure to diesel exhaust and DEPs, and elevated expression and concentrations of inflammatory mediators have similarly been observed in the respiratory tract after diesel exhaust and DEP exposure (Ghio et al. 2012) Earlier studies showed that DEPs also cause respiratory symptoms and modify the immune response in subjects with atopic disease and can interact with aeroallergens to enhance antigen-induced responses (Diaz Sanchez et al. 1997). Even though an increased sensitivity of asthmatic individuals to the proinflammatory effects of DEPs has not been confirmed, some studies have shown a bigger effect of exposure to high-traffic roads in asthmatics compared to nonasthmatic subjects, also accompanied by increases in levels of biomarkers of neutrophilic inflammation (McCreanor et al. 2007).

1.09.4 Possible Effects of Climate on Respiratory Allergy

The effects of climate on allergic diseases in general (Shea et al. 2008), especially respiratory allergic diseases (D'Amato and Cecchi 2008; Ayres et al. 2009; US EPA 2008), have recently been reviewed. Taking into account the main environmental factors affecting respiratory diseases and their plausible changes under a subset of different possible future regional and local climate conditions, some negative effects are possible. The impact of pollen, spores, and pollutants might be greater, with children possibly being the more exposed and susceptible population (Schmier and Ebi 2009).

Climate might affect the prevalence of respiratory allergic diseases through an effect on important environmental factors for these diseases, such as aeroallergens and pollutants. Climate variability and any longer term change affect pollen and spore production by plants and fungi as well as different phenological events and, at the same time, the different aerobiological processes (emission, dispersion and/or transport, and deposition) of aeroallergens.

Plant biology is directly affected by rising carbon dioxide (CO_2), (CO_2 being the sole supplier of carbon for photosynthesis) and by temperature and water availability, among the most relevant environmental factors affecting phenology. Since the concentration of atmospheric CO_2 is projected to increase in the next decades, a number of effects on plants involved in human health can be anticipated in the future (Ziska et al. 2009).

Climate, including possible changes in regional and local climate statistics as well as the increase in the atmospheric concentration of CO_2, could affect the allergic population

Table 1 Examples of climate phenomenon related to air pollution and allergens and possible health impact

Examples of climate phenomenon	*Possible effects on air pollutants and allergens*	*Allergic effects*
Fewer cold days and nights over most land areas	None	Possible impact on asthma through reduction of airways infections
Warmer and more frequent hot days and nights over most land areas	● Earlier pollen season onset ● Increased pollen season duration ● Increased pollen production ● Altered plant and pollen distribution (invasion of plants)	Increased asthma and rhinitis symptoms
Warm spell and heat waves	Air pollution ● Increased levels of particulate matter and O_3	Increased risk of development and exacerbations of allergies
	Pollen ● Earlier pollen season onset ● Altered plant distribution (invasion of plants and neophytes) ● Increased pollen production/content/allergenicity ● Increased pollen season duration	Increased risk of development and exacerbations of pollen allergies
Heavy precipitations	Increase in dampness and molds	Increased risk of development and exacerbations of allergies
Drought increases	Altered plant distribution (invasion of plants)	Increased risk of development and exacerbations of pollen allergies
Extreme weather events (wind)	Long-distance transport of pollens	Increased risk of development and exacerbations of pollen allergies

through (1) increased levels of air pollutants and (2) altered spatial and temporal distribution of allergens (Table 1). In this chapter, we summarize and discuss evidences on the interactions among climate, air pollution, airborne allergens, and respiratory allergy.

1.09.4.1 Possible Effects on Pollutant Levels

Climate factors influence regional weather regimes (wind patterns, and amount and intensity of precipitation, and air temperature) and, as a consequence, severity and frequency of air pollution episodes (Ayres et al. 2009). Moreover, it can affect anthropogenic emissions (e.g., increase in energy demand for space cooling) and enhance urban heat island effect, inducing an increase in some secondary pollutants (i.e., ozone). Finally, there can be an indirect effect on natural sources of air pollutant (e.g., decomposition of vegetation, soil erosion, and wildfires) (Confalonieri et al. 2007).

As tropospheric ozone is formed in the presence of UV and high temperatures, its concentrations increase with the increase of air temperature. In fact, tropospheric ozone concentrations are increasing in most regions (Chen et al. 2004), and this trend is expected to continue over the next 50 years (Prather et al. 2003).

Heterogeneous composition of PM, however, makes a projection of the effects of climate on its concentration very difficult. The crucial importance of local climatic conditions makes the projections even more troublesome and challenging. Other sources of PM can be affected by changes in temperature and precipitation, such as forest fires (Moore et al. 2006).

SO_2 and NO_x oxidize in the atmosphere in reaction with water vapor in air to form sulfuric acid and nitric acid, respectively, and the oxidation rate is accelerated by higher temperature. An overall warming climate might induce an increasing potential of acid deposition (e.g., acid rain) (Bernard et al. 2001) that might be counterbalanced by a decrease of SO_2 emissions, for example, for public electricity and heat production, as shown in Europe and the United States (EEA 2007; EIA 2007).

Despite the above-mentioned limitations and difficulties in projecting other variables, such as population growth, economic development, energy use, and production, climate has the potential of inducing an increased concentration of all air pollutants, PM, and ozone in particular. However, there is a possibility of a decrease in demand of heating systems during milder winters. Hopefully, measures aimed at reducing air emissions of air pollutants will contribute to mitigate the negative effects.

1.09.4.2 Possible Effects on Airborne Allergens

Weather variables, mainly air temperature, sunlight, and rainfall, together with CO_2, are among the main factors affecting phenology (i.e., the times of the appearance of first leaves, first flowers, autumn leaf coloration, and so on) and, mostly important from an allergological point of view, pollen production per plant. In addition, weather patterns influence the movement and dispersion of all aeroallergens in the atmosphere through the action of wind and rainfall and depending on the atmospheric stability.

Current data suggest that there are changes in duration, intensity, and start of the pollen season, even though substantial differences are observed among taxa, species, and

Table 2 Possible changes in airborne allergenic pollen levels and allergenic plants distribution in Europe

Examples of possible effects of climate in the coming decades	*Pollen involved*
Earlier start of pollen season (western and Baltic Europe)	Mugworth, pellittory, grass, birch
Extended duration of pollen season	Summer and late flowering species
Increase of long distance episodes	Ragweed, birch
Increased pollen allergenicity	Ragweed
Increased pollen production	Ragweed, birch

Source: Modified from D'Amato, G., L. Cecchi, 2008 Aug: Effects of climate change on environmental factors in respiratory allergic diseases. *Clin. Exp. Allergy*, **38** (8), 1264–1274.

geoclimatic areas (Table 2). However, the extent of evidence varies from one to the other. A number of studies indicate a clear association between climate and significant advances in spring flowering times with subsequent shifts in plant phenology (Fitter and Fitter 2002; Cleland et al. 2007). The availability of extensive time series of pollen count in the air and field phenological observations in Europe provided an impressive amount of data on these possible changes in allergenic plants. Preliminary studies performed in other continents confirmed these findings (Levetin & Van de Water 2008).

Pollen allergenicity is associated with allergen concentrations. Some experimental and field studies report an increase in allergen content of pollen produced by plants growing in higher temperatures and in CO_2-enriched atmosphere (Ziska and Beggs 2012).

The concentration of Amb a 1, ragweed's major allergen, in protein extracted from the pollen of *A. artemisiifolia*, increases in a CO_2-enriched atmosphere (of which the levels were selected based on expected anthropogenic emissions in the coming decades) (Singer et al. 2005). However, in a field study, a significantly higher quantity of antigenic protein was extracted from pollen at the rural site (a low-CO_2 area) relative to an urban site (a high-CO_2 area), despite the fact that in the urban site, pollen production was significantly higher (Ziska et al. 2003). Similar findings have been published about the effects of higher temperature on pollen production and allergen content of the major allergen, Bet v 1 (Ahlholm et al. 1998). Recent studies show that the allergen content of pollen of birch (Buters et al. 2010), pellittory (Jato et al. 2010), and olive trees (Moreno-Grau et al. 2006) vary with location, year of collection, and cultivars, suggesting that the variation of allergen content is affected by several environmental and genetic factors.

Nearly all species and regions analyzed have shown significant changes in seasonal onset that are coincident geographically with an increase in temperature (Cecchi et al. 2010). However, in some cases, local climatic conditions played an important role. For example, data provided by the International Phenological Gardens network showed that spring events advanced by 6 days, the highest rate of phenological changes being observed in Western Europe and the Baltic regions (Menzel and Fabian 1999). Conversely, phenological trends appear to be different in eastern parts of Europe, sometimes showing a 1- to 2-week delayed onset of the phases (Ahas et al. 2002). Duration of the pollen season is also extended, especially in summer and in late flowering species (Frei and Gassner 2008).

Urban areas provide an interesting model for analyzing the effect of an increase in air temperature and CO_2 concentrations. Some preliminary results show an earlier start of flowering in urban compared to rural areas, for example, *Ambrosia* (Ziska et al. 2003) and *Platanus acerifolia* (Mimet et al. 2009). Experimental data support the above-mentioned observations, as indicated by a meta-analysis to assess the effects of CO_2 enrichment (500–800 ppm) on reproductive organs, showing that total plant mass increased by 31% under elevated CO_2 concentrations compared with controls (Jablonski et al. 2002), and in experimental studies on *A. artemisiifolia* (ragweed) in which both pollen production (Rogers et al. 2006) and floral spikes per plant were increased when CO_2 levels are elevated (Wayne et al. 2002).

Increases in temperature are also inducing an altitudinal and longitudinal plant migration (Cecchi et al. 2010), thus changing plant species diversity and density, and then provoking habitat alteration or fragmentation. These changes could expose allergic population to new allergens. As an example, pollen data from the National Allergy Bureau in the United States and the Aerobiology Research Laboratories in Canada demonstrated that the duration of the ragweed pollen season has been increasing with the increase of latitude (Ziska et al. 2011). However, additional factors are accelerating the migration of this invasive allergenic plant. For example, in the eastern European countries, the expansion of ragweed seems also to be associated with major socioeconomic transitions that occurred during the inception and collapse of communism, which contributed to increased areas of disturbed land (suitable for ragweed proliferation) (Kiss and Béres 2007). A northward shift of distribution of birch, olive trees, and ragweed and a corresponding increase in height of the altitudinal tree line have been projected by Emberlin (1994).

Trends of grass pollen are more heterogeneous, possibly because of the numerous species that contribute to pollen counts in the different countries. In general, warming and increased CO_2 concentrations are thought to favor a northward expansion of some species of grasses (Olesen and Bindi 2002). However, a two-phase trend in the 38-year pollen dataset of Basel, with a decreasing pollen count for grass and birch in the period 1991–2007, has been shown by Frei and Gassner (2008). A declining trend is also reported for yearly Poaceae pollen counts in Leiden (the Netherlands) (Jäger et al. 1991), in London and Derby (United Kingdom) (Emberlin et al. 1993, 1999), in Parma (Italy) (Ridolo et al. 2006), and, even with a smaller dataset, in two Spanish studies (Gonzalez Minero et al. 1998; Jato et al. 2009).

Damp housing has been related to asthma in both children and adults, potentially with a high economic impact. Evidence from epidemiologic studies and meta-analyses showed indoor dampness and mold to be associated consistently with an increase in asthma prevalence and exacerbation, current and ever diagnosis of asthma, wheeze, and allergic rhinitis (Mendell et al. 2011). Associations were found in allergic and nonallergic individuals. Evidence strongly suggested causation of asthma exacerbation in children. Although a role for allergic sensitization associated with fungal exposure is plausible, the

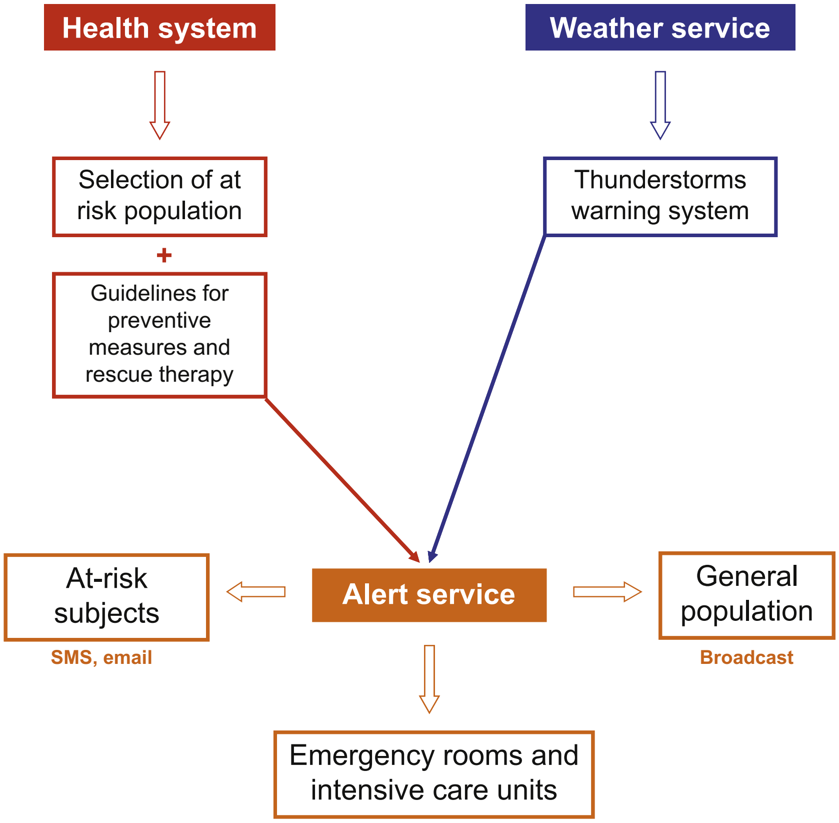
Health system
Weather service
Selection of at risk population
+
Guidelines for preventive measures and rescue therapy
Thunderstorms warning system
At-risk subjects
SMS, email
Alert service
General population
Broadcast
Emergency rooms and intensive care units

Figure 1 Setup of a warning system for thunderstorm asthma in the at-risk countries.

evidence is less strong than in the case of asthma and rhinitis. The potential for exposure to other bioactive molecules associated with dampness, such as endotoxins, volatile organic compounds, and mycotoxins, may also be relevant.

1.09.5 Case Study: 'Thunderstorm Asthma'

Since the first report in 1985 (Packe and Ayres 1985), several episodes of outbreaks of asthma, with a significant increase in emergency room visits and some cases of near-fatal asthma, were associated with thunderstorms in several parts of the world (Bellomo et al. 1995; Marks et al.; Venables et al. 1997; Girgis et al. 2000; Wardman et al. 2002; D'Amato et al. in press). Mechanisms underlying the so-called 'thunderstorm asthma' are still unclear. Studies published so far support the hypothesis that several mechanisms come into play. Weather conditions such as rain or humidity may induce fragmentation of pollen grains, which releases allergenic biological aerosols into the atmosphere (D'Amato et al. 2007) Grass pollen and spores are the aeroallergens mostly involved in thunderstorm asthma episodes reported so far (Pulimood et al. 2007), but other pollen types could act as triggers of these outbreaks (D'Amato et al. 2008). Pollen involvement has been objectively shown in an Australian study with the arrival of a thunderstorm outflow accompanied by a large increase in the concentration of ruptured pollen grains in ambient air, thus concentrating pollen grains at ground level (Marks et al., 2001).

Heavy rainfall episodes, including thunderstorm, may increase in terms of intensity and frequency in the next decades, which may increase gradually the number and severity of asthma attacks both in adults and children (Solomon et al. 2007). Even if thunderstorm asthma outbreaks usually involve a small number of patients, asthma attacks are often severe and sometimes near fatal. The public health impact of thunderstorm-related asthma may be not be negligible. To this regard, it might be considered as a useful case study of possible future risks for the population related to possible changes in regional and local climate and of possible adaptation strategies to reduce those risks.

1.09.5.1 Adaptation Strategies

In the case of thunderstorm asthma, adaptation strategies should essentially be based on a warning system.

The setup of a thunderstorm watch/warning system for an asthmatic population (Figure 1) involves the following:

1. *Selection of 'at-risk' countries, that is, those countries with a high prevalence of asthma and high risk of thunderstorms*. Presence of certain types of pollen (grass, pellittory, and olive tree) and spores has been shown to increase the risk of asthma outbreaks during a thunderstorm. Scientific literature indicates Europe (mainly Italy and United Kingdom) and Australia as the more at-risk areas of the world.
2. *Implementation of a weather service with a thunderstorm warning system*. A focused warning system should be able to

forecast thunderstorms, possibly indicating the risk of occurrence of an extreme event, for example, expressed as a percentage of risk, like in the case of rainfall.

3. *Identification of at-risk populations*. Subjects with asthma and known sensitization to one or more of the 'culprit' pollen and spores represent the more at-risk population and should be considered the main target of a warning system. As subjects with allergic rhinitis and without previous asthma may experience severe bronchoconstriction, they should also be included. Asthmatics who have already experienced severe asthma attacks are possibly at higher risk, as recently described by D'Amato et al. 2012.
4. *Measures aimed at reducing the risk of asthma attacks*. At-risk subjects should be advised to stay indoors and to close the windows when a thunderstorm is approaching. As previous studies have shown an increase of severe asthma attacks among poorly controlled subjects, they should be provided with a plan of treatment, including a step-up in the treatment and rescue therapy.
5. *Dissemination of information*. When a defined threshold of risk of a thunderstorm is forecasted, the population at risk is alerted via broadcasts, text messages, and e-mail. Emergency rooms are also alerted and prepared for a possible increase of life-threatening asthma attacks.

1.09.6 Conclusions

Possible effects of climate on prevalence and exacerbations of allergic respiratory diseases are complex and difficult to be projected. The reason behind this uncertainty is the complexity of environmental factors that play a role in the etiopathogenesis of both rhinitis and asthma. Among these factors are airborne allergens and pollutants, even interacting at different levels and affected by meteorological conditions that influence their concentration in the air. Climate factors affect all the processes of production, dispersion, and diffusion of pollen and atmospheric concentration of pollutants. Almost all studies published so far indicate that local conditions are of great importance, making predictions more difficult.

In summary, current knowledge suggests a potential negative effect of climate in the coming decades on the environmental factors involved in the mechanisms of development and exacerbations of allergic respiratory diseases. To this regard, the so-called 'thunderstorm asthma' can represent a useful model of an extreme event with public health implications. Even if currently rare, these events may increase in some areas of the world in the next decades; so, adaptation strategies are needed in order to reduce the number and severity of asthma attacks.

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1.10 Precipitation and Flood Hazards: Health Effects, Risks, and Impacts

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1.10.1 Precipitation and Flood Risk

Floods are the most frequent natural disasters, and have caused over 200 000 deaths and affected over 2.8 billion people over the last 30 years (Centre for Research on the Epidemiology of Disasters). The most common cause of flooding is long-lasting or intense heavy rainfall, resulting in high river runoff (Few et al. 2004). Rainfall over a long period may cause a gradual rise in river levels that can result in the overflow of rivers and inundation of surrounding areas. Intense rain from storms and cyclones, on the other hand, may cause rapid runoff and sudden flash floods across river basins. Floods can also be caused by tidal and wave extremes such as storm surges or tsunamis, the thawing of ice or structural failures such as breaches of dams or sea defenses (Few et al. 2004).

Reports indicate that floods may be intensifying and that this trend could continue in the future (Easterling et al. 2000; Milly et al. 2002). Regional changes in precipitation characteristics (e.g., total amount, variability, and frequency of extremes) have been suggested to increase the frequency and intensity of floods (Watson et al. 1997). The effects of floods on population health may be of significant concern.

1.10.2 Health Impacts of Floods and High Rainfall

1.10.2.1 Diarrhea

Increased transmission of diarrheal diseases is possible during flood and postflood conditions. In high-income countries, the risk of diarrhea due to flooding is considered to be low (Hunter 2003; Ahern et al. 2005), although a study in the United Kingdom reported an increased risk of gastroenteritis for flood-exposed individuals (Reacher et al. 2004). A cohort study performed in the United States found that house or yard flooding was associated with an increased risk of gastrointestinal illness (Wade et al. 2004). Self-reported diarrhea was used as an outcome measure in these two studies.

In low-income countries, where water supply, sanitation systems, and the causative agents of diarrhea are likely different from those in high-income countries, postflood increases in cholera (Sur et al. 2000), rotavirus (Ahmed et al. 1991; Fun et al. 1991), cryptosporidiosis (Katsumata et al. 1998), and nonspecific diarrhea (Woodruff et al. 1990; Siddique et al. 1991; Biswas et al. 1999; Mondal et al. 2001; Kondo et al. 2002; Kunii et al. 2002) have been documented. In one instance, an area outside a flood-control embankment had an 18% higher mortality rate compared with the rate inside the embankment, suggesting an adverse effect of flooding on diarrheal mortality (Ali et al. 2002). A study of a diarrheal epidemic during floods in Bangladesh provided good evidence for an increase in diarrheal cases due to some pathogens (Schwartz et al. 2006). During three consecutive flood-related epidemics in 1988, 1998, and 2004, the mean number of cases due to *Vibrio cholerae*, *Shigella*, *Salmonella*, *Entamoeba histolytica*, *Giardia lamblia*, and rotavirus increased compared with seasonally matched nonflood periods. *Vibrio cholerae* played a primary role in flood-related epidemics, because it was the only pathogen with an increased proportion of cases during the flood compared with the nonflood period. Schwartz et al. also reported that the cases during flood-related epidemics were older and of lower socioeconomic status than those in nonflood periods.

An episode analysis of the 1998 flood in Bangladesh revealed that during the flood, the number of noncholera diarrhea cases was almost two times higher than expected, while the number of cholera cases was almost six times higher than expected (Hashizume et al. 2008a, 2008b). In the postflood period, the risk of noncholera diarrhea was significantly higher for those with a lower educational level, who lived in a household with a nonconcrete roof, who drank tube-well water (versus tap water), or who used a distant water source or unsanitary toilets. These results suggest that those with low

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socioeconomic status and/or poor hygiene and sanitation were most vulnerable to flood-related diarrhea. The risk of cholera was significantly higher for those drinking tube-well water and those using unsanitary toilets. Another study also reported that populations with poorer hygiene and sanitation or lower socioeconomic status had a greater risk for diarrhea (Kunii et al. 2002).

Floods adversely affect water sources and supply systems, as well as sewage and waste disposal systems (Parker and Thompson 2000). For example, the waste disposal system in Dhaka was almost completely ineffective during the major flood of 1998 (Nishat et al. 2000), and a number of tube-wells were covered by floodwaters and contaminated (Rashid 2000). Many flood-affected people were displaced and took refuge in temporary shelters (Karim et al. 1999). Some of the shelters were extremely crowded (Karim et al. 1999), and deteriorated environmental conditions were observed in shelters and slums (Ahmed et al. 1999). These observations imply that hygiene and sanitation practices in the city were extremely disrupted, and it is likely that the transmission of enteric pathogens increased during the flood.

The effects of flooding on diarrheal incidence tend to fall disproportionately on individuals at socioeconomic disadvantage and those with poor hygiene and sanitation practices. Public health measures to prevent or reduce the burden of diarrhea in these vulnerable populations (e.g., provision of clean potable water and sanitary toilets, hygiene and sanitation education, and temporary measures to reduce pathogen concentrations in drinking water such as chlorine tablets and using a sari cloth as a filter) must be stressed during a response to flooding. These strategies may also be important measures in adapting to a future climate (World Health Organization 2003a, 2003b).

Many studies have reported a seasonal coincidence of peak diarrhea incidence with the rainy season in tropical regions (Cairncross and Feachen 1993). For example, a cohort study with daily surveillance for 1 year in rural Thailand showed that both dysentery and watery diarrhea rates peaked during the early rainy season (Sutra et al. 1990). In another rural Thailand study, a high incidence of acute diarrhea occurred at the beginning of the rainy season (Pinfold et al. 1991). However, these observational studies did not address a direct association between rainfall and diarrhea, meaning that calendar time effects (e.g., long-term trends and season) could potentially confound the results.

A study of 548 outbreaks recorded from 1948 to 1994 in the United States reported a relationship between outbreaks of waterborne diseases and heavy rainfall events (Curriero et al. 2001). Fifty-one percent of waterborne disease outbreaks were preceded by extreme rainfall events. The analysis stratified by water contamination source, and showed the strongest association between outbreaks due to surface water contamination and extreme precipitation during the month of the outbreak. This finding suggests that the route of exposure was ingestion of contaminated drinking water, which was likely contaminated by flooding or rainfall.

Only a few studies quantify the relationship between rainfall and diarrhea while allowing for potential confounding by temperature and calendar time effects. A time-series study in Fiji reported that high rainfall was associated with significant increases in diarrhea in the same month, but decreased diarrhea in the following month (Singh et al. 2001). After allowing for the effects of long-term trends and seasonal patterns, the reported incidence of diarrhea increased by 2% (95% confidence interval (CI): 1.5, 2.3) for each $1\ \mathrm{kg\,m^{-2}\,min^{-1}}$ increase in rainfall above the median value and by 8% (95% CI: 7.6, 9.2) for each $1\ \mathrm{kg\,m^{-2}\,min^{-1}}$ decrease in rainfall below the median. The authors suggested that high rainfall initially flushes fecal contaminants from pastures and dwellings into water supplies, but that continued rainfall could lead to a subsequent improvement in water quality.

1.10.2.1.1 Cholera

Cholera dynamics in endemic regions show regular seasonal cycles. An annual bimodal distribution is observed in Bangladesh (Pascual et al. 2002), while annual single peaks are seen in South America (Codeco 2001), India (Jesudason et al. 2000), and Pakistan (Sheikh et al. 1997). This clear seasonality suggests that weather factors play a role, either directly or indirectly through intermediate pathways. However, little empirical evidence of the role of these weather factors has been presented.

Glass et al. (1982) investigated the relationship between cholera peaks and monthly river level, temperature and rainfall using historical data from 1966 to 1988 in Matlab, Bangladesh. They found a cholera peak in the postmonsoon season and a smaller peak before the monsoon season, and reported that "variations in the time of onset, time to peak incidence, or time of maximum rise and fall in the number of cholera cases could not be forecast by changes in the timing of environmental parameters such as peak rainfall or onset of the monsoon, high and low river water levels, or rise and fall in the mean peak or low monthly temperature".

Pascual et al. (2002) suggested that high rainfall during the monsoon season in Bangladesh could reduce cholera cases by diluting the concentration of *V. cholerae* in aquatic environments and reducing the salinity levels of surface water below the optimum requirements for *V. cholerae* survival. This hypothesis was inferred from the observation of a marked depression in cholera incidence during the monsoon season. In contrast, cholera peaked during the monsoon season in dryer areas of India (Pascual et al. 2002). The incidence of cholera is influenced by primary transmission of *V. cholerae* from an aquatic environmental reservoir in endemic regions (Lipp et al. 2002), and a variety of physical and biological parameters are likely to influence the growth and survival of *V. cholerae* in the environment (Faruque et al. 2005a, 2005b). The effect of rainfall on the seasonality of cholera may depend on average rainfall levels (Pascual et al. 2002).

Cockburn and Cassanos (1960) proposed that ponds in Bangladesh were the main sources of infection in the community, hypothesizing that if the pH in the ponds were sufficiently elevated, *V. cholerae* could have a survival advantage over other bacteria. They showed a relationship between elevated pH and the onset of cholera cases, which was also related to season, sunlight, temperature, and rainfall. In this hypothesis, algae sequestration of CO_2 during photosynthesis drove the temporal pH changes. The largest pH changes occurred with elevated temperatures, low turbidity, and sufficient light. According to the Cockburn and Cassanos hypothesis, when high rainfall muddies and dilutes pond water the pH will not rise, and *V. cholerae* will lose its survival advantage.

Lipp et al. (2002) proposed a cholera model of hierarchy consisting of abiotic factors, phytoplankton and aquatic plants, zooplankton and transmission to humans. *Vibrio cholerae* growth rates increase in aquatic environments at warm temperatures in combination with high pH conditions and blooms of phytoplankton, aquatic plants, or algae. Sunlight, temperature, and nutrients in the aquatic environment influence the growth of phytoplankton and aquatic plants that in turn alter the dissolved O_2 and CO_2 content of the water, changing the pH of the surrounding water. High phytoplankton production produces food for zooplankton, to which *V. cholerae* attaches for protection from the external environment and proliferates.

A time-series study using hospital surveillance data in Bangladesh reported that for a 10 mm increase above a threshold of 45 mm in average rainfall over current and previous 8 weeks, the weekly number of cholera cases increased by 14% (Hashizume et al. 2008a, 2008b). Conversely, the number of cholera cases increased by 24% for a 10 mm decrease below the same threshold of average rainfall over the current and previous 16 weeks. River levels partly explained the association between high rainfall and the number of cholera cases; after controlling for seasonal and between-year variations and rainfall, the number of cholera cases increased by 137% for a 1 m increase in average river level above a threshold of 4 m over current and previous 4 weeks.

Phage predation of *V. cholerae* has also been reported as a possible factor influencing seasonal cholera epidemics in Bangladesh. Faruque et al. suggested that epidemics would most likely begin in periods of low phage concentration (e.g., after floods and the monsoon season). This suggestion stemmed from the observation of an inverse correlation between the environmental concentration of vibriophages and the presence of susceptible *V. cholerae* strains in water (Faruque et al. 2005a, 2005b). The authors also proposed that phages play a predominant role in ending cholera epidemics, although a recent simulation study did not support this hypothesis (King et al. 2008). More research on phage concentrations and cholera epidemics is needed to confirm or deny the phage predation hypothesis.

Huq et al. (2005) reported a time-series analysis using clinical and environmental data (including water temperature, air temperature, water depth, rainfall, pH, salinity, water conductivity, dissolved O_2, bacteria, and copepod counts in water samples) collected at biweekly intervals in four rural locations in Bangladesh for 4 years. They found a significant negative association between rainfall and cholera incidence in some locations, with different lags of 0–8 weeks.

Apart from seasonality, cholera dynamics in endemic regions also show marked interannual variability. In the analysis of historical data from former British India, rainfall was associated with cholera's spatial distribution (Pascual et al. 2002). Average annual cholera mortality in nine provinces of former British India was higher in provinces with higher annual rainfall.

Koelle et al. (2005) reported environmental determinants of interannual cholera cycles in rural Bangladesh while taking intrinsic host immunity into account. The interannual variability of cholera showed a strong inverse relationship with monsoon rains and Brahmaputra River discharge over long periods of time (over 7 years), Conversely, the interannual variability of cholera showed a positive relationship with flood extent in Bangladesh, sea surface temperatures in the Bay of Bengal, and the El Niño Southern Oscillation (ENSO) over shorter periods of time (less than 7 years). The authors suggested that understanding the interannual cycles of cholera requires a combined analysis of both environmental and intrinsic host factors.

In summary, high rainfall is likely to influence the growth, survival, and proliferation of *V. cholerae* in aquatic environments through a complex interaction of factors including temperature, sunlight, salinity, pH, phytoplankton, and zooplankton in the aquatic environment. From the observation of a reduction in cholera incidence during the monsoon season in Bangladesh, high rainfall has been suggested to reduce cholera cases by diluting *V. cholerae* and by reducing water salinity levels below the requirements for pathogen survival. In the analyses of interannual cholera variability, rainfall, particularly in the monsoon season, is suggested to be negatively associated with cholera incidence at longer lags. However, there is little epidemiological evidence for a seasonal influence of rainfall on cholera incidence that also takes seasonally varying factors into account.

1.10.2.1.2 Cryptosporidiosis

A number of outbreak investigations of cryptosporidiosis in the United Kingdom and the United States have suggested that a contributing factor in the outbreaks was drinking or recreational water contamination by heavy rainfall. In a 1993 cryptosporidiosis outbreak in Milwaukee, more than 400 000 people were estimated to have developed symptomatic gastrointestinal infections (Mac Kenzie et al. 1994), although this number has been criticized as a 10-fold overestimation (Hunter and Syed 2001). Outbreak investigations in Ayrshire, Scotland, concluded that irregular seepage of oocyst-containing water increased during heavy rains and was the cause of the waterborne outbreak through water tank contamination (Smith et al. 1989). In an outbreak in Warrington, England, cases were strongly associated with drinking unboiled tap water from contaminated sources (Bridgman et al. 1995). In this outbreak, one water source was found to drain surface water directly from a field containing livestock feces. Similarly, an outbreak investigation in Bradford, England, reported that heavy rainfall was recorded in the catchment area of the reservoir supplying raw water to the water treatment facility immediately prior to the probable time of infection (Atherton et al. 1995). Outbreaks associated with recreational use of contaminated rainwater runoff have also been reported in New Jersey, the United States (Kramer et al. 1998).

Seasonal patterns of cryptosporidiosis vary from country to country. In temperate regions, the peak incidence of cryptosporidiosis is seen in spring to early autumn. In the United Kingdom, seasonal peaks of cryptosporidiosis have occurred in both spring and autumn (Public Health Laboratory Service Study Group 1990). In North America, peak incidence occurs in summer and early autumn (Sorvillo et al. 1998; Dietz et al. 2000; Naumova et al. 2000; Hlavsa et al. 2005; Laupland and

Church 2005). In tropical regions, the seasonal peaks often coincide with periods of high rainfall. A hospital-based study conducted in an urban setting in Gambia reported that peak prevalence of *Cryptosporidium*-associated diarrhea were recorded during rainy months, while no case was recorded during dry months (Adegbola et al. 1994). Similarly, a 4-year cohort study of children born in an urban slum in Brazil showed that the percentage of *Cryptosporidium*-associated diarrhea ranged from 16.4% during the rainiest month of the year to 0% during 4 of the 5 driest months of the year (Newman et al. 1999). In these studies, rainfall exacerbation of low-level water source contamination was suggested as a cause of seasonal peaks during the rainy season. The pattern of the highest number of cases occurring during rainy months has been observed in other tropical countries, including Bangladesh (Rahman et al. 1990), India (Nath et al. 1999; Gambhir et al. 2003), Indonesia (Katsumata et al. 1998), Uganda (Tumwine et al. 2003), and Guatemala (Bern et al. 2000). However, these studies did not control for season, so it is possible that rainfall is a marker for other environmental or behavioral factors that are more often observed in rainy seasons. Seasonal patterns of cryptosporidiosis may also indirectly reflect the interaction of rainfall with agricultural events such as the application of animal and human excreta to pasture as fertilizer (Casemore 1990; Meinhardt et al. 1996).

Lake et al. (2005) conducted a time-series analysis of the relationship between the monthly cryptosporidiosis rate and weather and river flow in England and Wales allowing for seasonal effects. Between April and July, the period when many newborn animals are on the land, the cryptosporidiosis rate was positively associated with river flow in the same month, after controlling for seasonal variations, rainfall and temperature. The authors suggested that high water saturation of the land during this season might be related to the efficient transportation of *Cryptosporidium* into river water by runoff. However, from August to November, warm and dry weather during the previous month was associated with cryptosporidiosis rates, and the authors hypothesized that *Cryptosporidium* falling onto the dry soil likely builds up and is effectively transferred by runoff into river water.

Naumova et al. (2005) reported a time-series analysis of the relationship between the weekly cryptosporidiosis rate and precipitation in northwestern England. After controlling for seasonal variations, the weekly cryptosporidiosis rate increased by 27% (95% CI: 21, 33) if the cumulative rainfall for the prior week was at the 75th percentile.

In summary, there is a clear link between high rainfall events and outbreaks of cryptosporidiosis through drinking or recreational water contamination. Seasonal cryptosporidiosis peaks and high rainfall periods coincide in tropical regions. This could be because of water source contamination by rainfall, but few of these studies have adjusted for seasonal variations. Only a few studies in the United Kingdom have measured rainfall effects on the incidence of cryptosporidiosis while allowing for seasonal variations.

1.10.2.1.3 Other Pathogens

The largest reported outbreak of *Escherichia coli* O157:H7 in the United States occurred in the State of New York in September 1999 and was linked to contaminated well water (Rose et al. 2001). Unusually heavy rainfall preceded by a drought coincided with this major outbreak. High soil saturation with water leading to the rapid transport of microbial agents was suggested as a factor that contributed to the well water contamination.

A large outbreak of bloody diarrhea caused by *E. coli* O157 infections in South Africa was reported in relation to heavy rainfall (Effler et al. 2001). Carriage of *E. coli* O157 by cattle, cattle deaths due to drought, and subsequent heavy rains that contaminated surface water were suggested as important factors contributing to the emergence of *E. coli* O157 in the region.

Shigella infections were found during the months of highest rainfall in the Philippines (Adkins et al. 1987). In contrast, shigellosis was more frequent during the cool, dry months in Bangladesh (Black et al. 1982; Stoll et al. 1982) and during hot, dry months in Israel (Vasilev et al. 2004). For *Salmonella*, a study in Guam showed that monthly rainfall was positively associated with the number of cases, especially in infants (Haddock and Malilay 1986). However, season was not adjusted in this study, so the rainfall could have been a marker for other environmental factors observed during the rainy season. Current knowledge is insufficient to make solid conclusions about the relationship between rainfall and Shigella, or between rainfall and Salmonella.

Outbreaks of other pathogens in private drinking water supplies have been reported in England and Wales (Said et al. 2003). Heavy rainfall was identified as a factor implicated with 4/25 outbreaks through 1970–2000. Two of these were attributed to *Campylobacter*, one to *Giardia*, and one to a mixture of *Cryptosporidium* and *Campylobacter*.

1.10.2.2 Acute Respiratory Infections

Acute respiratory infection (ARI) is a major cause of illness and death among populations displaced by natural disasters, particularly in children under 5 years of age (Watson et al. 2007). Lack of access to health care facilities and antimicrobial agents for treatment further increases the risk for ARI mortality. Risk factors among displaced populations include crowding, exposure to indoor cooking using an open flame, and poor nutrition. The reported incidence of ARI increased fourfold in Nicaragua in the 30 days after Hurricane Mitch in 1998 (Campanella 1999), and ARI was the most common cause of disease and deaths among those displaced by the 2004 Aceh tsunami (World Health Organization 2005). In Bangladesh, respiratory problems (14%) were the second highest cause of illness among those affected by flooding in 1998, following diarrhea (27%) (Kunii et al. 2002). ARI was also the second most common cause of illness (17%) and death (13%) among those affected by the 1988 flood in Bangladesh (Siddique et al. 1991). However, it is not clear whether the high number of ARI was caused by the flood or by a usual seasonal increase. Rigorous studies on the effect of flooding on ARI incidence are warranted.

1.10.2.3 Malaria

Rainfall is a major contributing factor to the increase of malaria cases (Kilian et al. 1999; Zhou et al. 2004; Thomson et al. 2005; Abeku 2007). In Ethiopia, higher rainfall was associated with increased malaria cases with saturating effects at higher rainfall levels. The association has been shown to have a shorter lag time in hot districts than in cold districts (Teklehaimanot et al. 2004). In Zimbabwe, rainfall and maximum temperature at a lag of 4 months fit a biological transmission model to malaria case data (Worrall et al. 2007). Malaria cases increased by 1.4%–10.7% per month for each 10 mm increase in monthly rainfall (with a 2–3 month lag) in the highlands of West Kenya (Hashizume et al. 2009). In contrast, interannual analysis of long-term data from Sri Lanka (1972–2005) showed negative correlations between malaria cases and rainfall in the districts with high annual rainfall (Briet et al. 2008). Meanwhile, no clear relationship was observed between rainfall and malaria incidence in central India (Singh and Sharma 2002).

Postflood increases of malaria transmission have been reported from Africa, Asia, and Latin America. For example, sharp increases in the number of malaria cases after 1982 El Niño-related flooding were reported in Latin American countries (Moreira Cedeno 1986; Russac 1986; Heddera 1987), and the number of malaria cases increased 1.5–2-fold following flooding in Mozambique in 2000 (Kondo et al. 2002).

Floods may also lead to geographical changes in malaria epidemic areas by changing breeding sites for vector mosquitoes. An epidemic of malaria was associated with changes in habitat following flooding in Costa Rica (Saenz et al. 1995). Malaria epidemics can also occur when people with little immunity move into endemic areas, although the displacement of large populations has rarely occurred as a result of acute natural disasters (Toole 1997).

1.10.2.4 Dengue Fever

High rainfall has been associated with dengue in Barbados (Depradine and Lovell 2004), Indonesia (Corwin et al. 2001), Mexico (Chowell and Sanchez 2006), Puerto Rico (Johansson et al. 2009), Taiwan (Chen et al. 2010), Thailand (Wiwanitkit 2006), Trinidad (Chadee et al. 2007), and Venezuela (Barrera et al. 2002). Floods can potentially increase the transmission of dengue. Standing waters caused by the overflow of rivers can act as breeding sites for mosquitoes, enhancing the potential for exposure of flood-affected populations to dengue (World Health Organization 2004). However, few studies have reported an association of dengue epidemics with flooding. No dengue infections were reported among relief workers in Puerto Rico after Hurricane George (1998) (O'Leary et al. 2002; Rigau-Perez et al. 2002), no outbreaks of dengue occurred after Hurricane Jeanne (2004) in Haiti (Beatty et al. 2007), and a low incidence of dengue was reported in flood-affected areas of Malaysia (Shaharom et al. 2009). After flooding in Thailand, an increase in the number of acute pyrexia cases was reported, of which 29% were dengue and 27% were leptospirosis (Pradutkanchana et al. 2003).

Hashizume et al. (2012) found a significant association between hospital visits for dengue and high river levels with a shorter lag time (0–5 weeks), and between hospital visit for dengue and low river levels with a longer lag time (6–19 weeks) in Dhaka, Bangladesh. The number of dengue cases increased when a prolonged low river level preceded a high river level. This result is consistent with a report that the number of dengue cases was higher when prolonged drought preceded the rainy season (Gagnon et al. 2001).

Although rainfall may increase the number of water containers available for mosquito breeding and lead to increased larval habitat, and vector population size (World Health Organization 2003a, 2003b), heavy rainfall may reduce mosquito numbers by destroying existing breeding sites and inhibiting the development of mosquito eggs or larvae (Patz et al. 1998). Additionally, differences in local water container types and water storage practices of the local population may lead to variations in the association between rainfall and *Aedes* mosquito abundance (Jansen and Beebe 2010).

1.10.2.5 Other Infectious Diseases

High rainfall and flooding increase the risk of leptospirosis by bringing the bacterial pathogen *Leptospira interrogans* and its animal hosts (e.g., rodents, dogs, and cats) into closer contact with humans. There have been reports of flood-associated outbreaks around the world including in the Philippines (Amilasan et al. 2012), India, Brazil (Ko et al. 1999; Barcellos and Sabroza 2001; Sarkar et al. 2002), Indonesia (Victoriano et al. 2009), Puerto Rico (Sanders et al. 1999), New Caledonia (Goarant et al. 2009), Nicaragua (Ashford et al. 2000), the United States (Gaynor et al. 2007), and Mexico (Sehgal et al. 2002; Leal-Castellanos et al. 2003; Kshirsagar et al. 2006; Bhardwaj et al. 2008).

In Brazil, the monthly number of leptospirosis cases increased by 0.55% per 1 mm increase in maximum daily rainfall of the month (Kupek et al. 2000). In India, peaks of disease onset were preceded by heavy rainfall 7–10 days previously (Pappachan et al. 2004). Periods of heavy rain followed by days of little or no rain were optimal conditions for leptospirosis outbreaks. Brazilian data have shown the presence of a threshold for the association between leptospirosis incidence and rainfall, supporting a hypothesis for the pathway: high rainfall → flooding (overflowing water) → exposure to water contaminated with urine from animals infected with *Leptospira* species (Codeco et al. 2008).

Environmental factors are thought to have been responsible for outbreaks of visceral leishmaniasis (VL) in Sudan in 1985 and 1986, where heavy rains favored sand fly breeding (el-Safi and Peters 1991). Franke et al. (2002) demonstrated a positive relationship between the incidence of VL and the ENSO, which affects rainfall patterns in Brazil. Franke et al. demonstrated that the previous year's mean Niño 3 index and the temporal trend accounted for approximately 50% of the variance in the annual incidence of VL.

Ben-Ahmed et al. (2009) performed a spatial analysis of VL in Tunisia, in association with climatic factors, and identified hot-spot regions of 35 districts located mostly in the semiarid bioclimatic zone. The incidence of VL was positively correlated with mean yearly rainfall and continentality index (difference between mean extreme values of high-summer and low-winter temperatures). Neronov and Malkhazova (1999) found a significant positive relationship between the incidence of zoonotic cutaneous leishmaniasis (CL) and soil moisture and temperatures in Turkmenistan. Broutet (1994) concluded that epidemics of CL in Brazil between 1986 and 1990 may have been attributable to climatic factors. In addition, the seasonal abundance of sand flies in southwest Asia has been shown to depend on temperature and humidity (Cross and Hyams, 1996; Cross et al. 1996).

Sand fly adults and larvae are sensitive to high temperatures and low humidity. In laboratory experiments, all adult sand flies died within 2 h at temperatures above 40 °C (Theodor 1936). Temperatures below 10 °C are also unfavorable for survival. In addition to temperature, laboratory studies have demonstrated that sand fly survival increases with relative humidity, and that larvae, pupae, and adult sand flies need a habitat with a constant, relatively high-humidity environment (Theodor 1936).

As discussed above, some evidence suggests an association between climatic variability (including events such as ENSO) and the incidence of leishmaniasis. However, climatic variability may have different impacts on the transmission of leishmaniasis in different regions of the world, depending on the particular vectors and the various *Leishmania* species involved.

1.10.2.6 Long-term Effects of Flooding on Mortality and Morbidity

There is little evidence on the long-term health impacts of flooding. A cohort study of people forced from their homes by flooding in 1968 in Bristol, England, found a 50% increase in the number of deaths in the year after the flood among those whose homes had been flooded, compared with people not forced from their homes (Bennet 1970). The number of clinic visits and hospital admissions was also higher in the year after the flood among those who had been affected by flooding compared to those who had not (Bennet 1970). However, an Australian study found no difference in mortality the year after a flood between those who had been affected by flooding and those who had not. However, the authors noted that those who had been affected made a greater number of visits to medical providers (Abrahams et al. 1976). Heightened psychological stress was thought to have played a part in the increase in visits in the two English and Australian studies. A study in England and Wales found a 10% relative reduction in mortality in flooded areas in years after flooding between 1994 and 2005. This finding may be due to the influence of population displacement from flooded areas (Milojevic et al. 2011). Another study in rural Bangladesh found no clear evidence of flood-related increases in mortality or diarrhea during or after the flood period in 2004, once preflood rate differences between flooded and nonflooded areas and seasonality were controlled for in the analyses (Milojevic et al. 2012). A space-time clustering of leukemia and lymphomas was reported in New York after 2 years of major floods in 1972 (Janerich et al. 1981). A study in China also showed higher malignant neoplasm mortality among the residents of flood-affected villages than among those of nonflooded villages in the year after a flood (Li et al. 2007). The standardized years of potential life lost rate for respiratory and circulatory diseases in the flooded village group were also significantly higher than those in the nonflooded village group (Li et al. 2007). The authors speculated that flood-related environmental contamination and psychological and physical stresses after the flood disaster may explain the findings. The long-term effect of floods on stress-related psychological disorders is an important public health issue (Ahern et al. 2005), but the adverse effects of experiencing a flood are not limited to mental health problems. There is clear evidence that chronic psychosocial stress contributes to the pathogenesis and development of coronary artery disease (Rozanski et al. 1999; Kubzansky et al. 2005). However, most of these studies had methodological limitations, in particular, a lack of preflood data, ambiguous exposure measurements, a lack of clinical diagnosis, and potential recall bias. Improved epidemiological research is needed on the long-term health impacts of floods.

1.10.2.7 Chemicals and Mold

There is a concern for potential long-term adverse effects of exposure to chemical contaminants, mold, and other toxic substances that may be present in homes after flood clean-up. A high concentration of mold was measured both indoors and outdoors in the New Orleans area 2 months after the flooding caused by Hurricane Katrina (Solomon et al. 2006). Repeated exposure to significant quantities of fungal material can result in respiratory irritation or allergic sensitivity in some individuals (Bush et al. 2006). There is evidence of a causal link between indoor dampness and upper respiratory tract symptoms, coughs, wheezing, and asthma symptoms in sensitive people (Institute of Medicine 2004).

1.10.2.8 Nutrition

Inadequate nutrition following disruption to incomes and food distribution systems is also important to note (Intergovernmental Panel on Climate Change 2001). There is evidence for an increase in both gastroenteritis and malnutrition during the rainy season in some countries (Draser et al. 1981). This may be associated with changes in food availability, which is lower in the rainy season (Minghelli et al. 1991; Bronson 1995). Higher opportunity costs of time for agricultural work, which is busiest in the rainy season, could disrupt the weaning practices of women (Draser et al. 1981). This could contribute to an increase in infant diarrhea and malnutrition in the rainy season. Long-term low nutritional status of children in flooded households compared to nonflooded households was reported in Bangladesh after the 1998 flood (del Ninno and Lundberg 2005). Fifty-one percent of households in urban areas in Bangladesh suffered income loss due to the flood, which resulted in decreased food consumption in the affected population (Ahmed et al. 1999). Persistent low nutritional in flood-affected populations may be related to the persistence of increased diarrhea incidence. In the presence of malnutrition, chronic or persistent diarrhea could arise secondary to other infections (Thapar and Sanderson 2004).

1.10.3 Health Impacts of Low Rainfall

Low rainfall and drought have been associated with increases in the incidence of diarrhea (Burr et al. 1978). This is particularly relevant where rainwater is collected for household uses. In such areas, hygiene and sanitary conditions seem to be closely related to rainfall (Pinfold et al. 1991). A water source may be utilized for an increasing number of uses during droughts, enhancing the risk of contamination (Lipp et al. 2002).

Increased concentrations of pathogenic agents in raw water supplies are suggested as a possible risk of gastrointestinal infections (Singh et al. 2001). Even where water treatment systems exist, falling water levels and reduced river flows during droughts increase the risk of cyanobacterial blooms, and make water treatment less effective, as levels of sediment and organic material increase (Leder et al. 2002).

The time-series study in Fiji revealed that, after controlling for season, low rainfall was associated with significant increases in diarrhea in the same month and the following month (Singh et al. 2001). Low rainfall was proposed to interrupt water supply and contribute to poor hygiene. Singh et al. also reported a cross-sectional study of the average annual rates of diarrhea and water availability, defined by precipitation per area of countries in the Pacific Islands. There was a negative association between water availability and diarrhea rates; that is, high water availability was associated with lower reported rates of diarrhea.

In temperate regions, rotavirus diarrhea peaks in winter and is rarely seen in summer. In the tropics, the seasonality is less obvious, while peak incidence is reported in cooler months, which often coincides with low rainfall. The peak was in winter, and the trough was in the rainy season in India (Kelkar et al. 1999), Brazil (Rosa et al. 2002), and Costa Rica (Hieber et al. 1978), and in the times of hot, dry weather in Kenya (Mutanda et al. 1984). In the United States, 45% more rotavirus hospitalizations were observed after the months with the least rainfall compared with the months with greatest rainfall (Brandt et al. 1982). Rotavirus outbreaks occurred after a period of prolonged low rainfall in Indonesia (Corwin et al. 2005). Although these findings suggest a seasonal coincidence of peak rotavirus activity with low rainfall periods, they do not provide evidence for a direct association of low rainfall with rotavirus diarrhea allowing for seasonal variations and temperature effects.

In summary, low rainfall has been suggested to increase the incidence of diarrhea through reduced water availability for domestic use and increased concentration of enteric pathogens in raw water supplies. However, few studies have taken into account potential confounding by season and temperature, indicating that further study is needed to determine the relationship between low rainfall and diarrhea.

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1.11 HIV/AIDS Disease Burden Complex in South Africa: Impact on Health and Environmental Resources, and Vulnerability to Climate

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1.11.1 Introduction

The Ottawa Charter for Health Promotion emphasized that health is not just a state or the object of living but should be considered as a vital resource for everyday life on which numerous services and deliverables depend. Without good health very little is achievable in the life of an individual or collectively in the context of a community (WHO Ottawa Charter 1986). In 1974, Lalonde postulated the early ideas conceptualizing the key determinants of an individual's health as being contingent on the following (Lalonde 1974):

1. The integrity of the human biological system, which includes genetic makeup, cellular senescence, and physiological processes. Aberrations in any of these compartments can result in human illness, pain, and suffering.
2. Healthy environments and ecological integrity. The emphasis on ecological services is paramount to a healthy living milieu for all human communities. These free ecological services represent clean air, fresh water, natural produce, climate stability, food and medicines, restraint on infectious diseases, leisure, and spiritual sanctuaries. These services are priceless; the opportunity cost cannot be valued by any stretch of imagination.
3. Healthy lifestyles. The aggregation of personal decisions (i.e., over which the individual has control) that can be said to contribute to, or cause illness or death. Some individuals may or may not be equipped with adequate information that promote healthy lifestyles, while others may be aware and choose to accept the risks associated with certain activities because they have limited options or are not prepared to forego certain self-indulgences in the interest of preventing illness.
4. Good or adequate health care facilities and policies, which consist of quantity, quality, and accessibility of such resources to the people and which operate at many levels of complexity.

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National health care strategies tend to place emphasis on conventional hospital-based health care facilities to improve health in communities. When disease burden in a community is high, these strategies can turn out to be economically draining (Harrison 2010b). While these are important, it is evident that majority of the causes of ill health are derived from the first three categories, human biology, environment perturbations, and lifestyle decisions, and are therefore amenable to public health, education awareness, and responsible environmental custodianship. It is argued that the tendency to focus both human and economic resources on category 4 (particularly secondary and tertiary health care facilities), while important, should not proceed at the detriment of preventative strategies incorporating healthy lifestyles and maintaining environmental integrity. This is the key message of the emerging policies for health care coverage for all South Africans, which emphasizes that the high cost of curative hospital centric health care systems are unsustainable into the future, especially in the light of expanding human health epidemics and contracting global economies. The blueprint suggests that more resources and logistics should be funneled into the public health and the primary health care setting (South African Policy Paper on the NHI, DOH 2011). Similar mitigating strategic plans are being promulgated by the South African Department of Environment in the sectors of clean water, quality air, and integral biodiversity (McMichael 2008; Midgley et al. 2008; 2010). These debates are pertinent to the current infectious burden of disease and uncertainty surrounding climatic trends and predictions in the Southern Africa subregion.

In this overview, the phenomenon of human immunodeficiency virus (HIV) infection and acquired immune deficiency syndrome (AIDS) is described in its historical and social context as the harbinger, while tuberculosis (TB), opportunistic infections, chronic inflammation, and specific HIV-related cancers are described as the sequel in a unique and predictable HIV burden of syndemic disease complex. This scenario has gripped South Africa in particular and the rest of the sub-Saharan African continent to varying degrees. The focus in this review is on attempting to put things in spatial, temporal, and relational perspective, elucidating the magnitude and impact of this complex burden of disease sequel as a significant threat to human health and environmental resources in the context of climate. The HIV burden of disease complex has a direct impact on ecosystem integrity and services, which creates an exacerbating cycle of events with feedback loops that perpetuate the epidemic through aggravating vulnerability and impoverishment.

South Africa has an extremely high burden of disease directly related to the emergence of the HIV epidemic in the 1980's, which has progressively escalated in a background of a large sector of the majority ethnic population dependent on subsistence agriculture and historically, geopolitically, and economically marginalized (Harrison 2010b). South Africa has an estimated population of about 55 million and an HIV population prevalence rate of 10%; Statistics South Africa estimates that the number of persons living with HIV (PLWH) is 5.4 million, which equates to 17% of the global burden in a country that contributes to only 0.7% of the world's population. It is suggested that for every person infected with HIV, four other people are affected. This means that 25 million people in South Africa are significantly affected directly or indirectly by the HIV epidemic. Sentinel rates, or the rates seen in the reproductive female population attending antenatal clinics, are on average 30% but can be as high as 47% in some provinces of South Africa. This means that a third to half of the reproductive age group of society are infected with HIV and will get ill eventually and succumb to a predictable HIV-related complication, leaving behind a host of affected dependents and loved ones (National Strategic Plan 2012; DOH; HSRC Annual report 2010/2011).

Embedded in this complex, South Africa is facing one of the worst epidemics of TB, including drug-resistant strains (TB DR-TB), which comprises multi-drug-resistant (MDR-TB) and extensively drug-resistant TB (XDR-TB). With a current per capita TB incidence in excess of 900 per 100 000 population, there has been a more than threefold increase from a decade ago (Lawn et al. 2009, 2011a,b; Middelkoop et al. 2009; Lawn and Zumla 2011; Lawn and Wood 2011). It is clearly understood that HIV and TB have a tandem relationship, and HIV is fueling the growing epidemic of TB in all its forms. Among newly diagnosed HIV patients, basic TB screening tools reveal that more than half have active TB. With more sophisticated technology, this figure is likely to be higher (National Strategic Plan 2012; World TB DOH 10 point plan progress report 2011).

1.11.2 Characteristics of South Africa's History That Lend Itself Favorably to the Spread of HIV and Urban and Rural Environmental Sensitivity

South Africa has a unique history, demographics, economic landscape, diversity of biomes, and complexity of cultures. There are 11 official languages spoken across nine provinces or states (South Africa Information 2012). Its historical legacy based on slavery and segregation created modern cities, farming communities, and a developed world industrial economy in the midst of disenfranchisement effected through forced removals and economic isolation of the indigenous African population over several centuries. The vast mineral wealth of the country created a workforce characterized by huge migrant labor with the consequences of fragmented family units and abnormal congregation of men in remote locations where most mines were located. Simultaneously, domestic city labor force, comprising mainly women, was required to service the affluent, mainly white, European colonial minorities in the cities. This created unplanned townships on the outskirts of major cities, which grew over time into sprawling informal settlements devoid of basic amenities or any form of environmental impact assessments. Movement of this labor force was regulated by strict security and movement laws. These settlements were meant to be temporary but conveniently ignored, and out of necessity they grew in a haphazard and unregulated manner to cater to the domestic and industrial workforce that fed the cities with cheap labor. Several mixed-race communities evolved in the process from the 'illegal' and sometimes forceful fraternization between the colonial land owners and the indigenous populations, slaves from other African countries and Asian indentured workers. Physical and sexual violence coupled with the abuse of alcohol were ingrained in the culture at several levels. The origin of South Africa's reputation as the rape capital of the world is heavily debated in social science forums (Jewkes et al. 2009).

South Africa attained independence in 1994 after a long and protracted violent and cruel resistance movement emanating out of these townships, facilitated by international isolation, eventually creating the opportunity for democratic governance. These historical precedents created perfect conditions that fueled the dramatic spread of HIV infection once introduced into the population. Unfortunately, many of these characteristics still prevail in many forms and guises. Naturally the HIV took off with a vengeance in the disenfranchised majority of the population. While South Africa has a wealthy historical colonially privileged minority subsector and now a new indigenous political elite, there is a rapidly growing middle class comprising previously disadvantaged ethnic groups, mixed and Asian races. However, the majority subsector live in poverty in the rural areas and township settlements in what is described as one of the most unequal economies in the world (New Growth Path Initiative website SA Treasury 2012). South Africa is predominantly a semiarid ecosystem and highly sensitive to changes in rainfall. Attempts to redistribute wealth in a more equitable manner coupled with the high burdens of disease, unpredictable weather pattern trends, and depression of global economies are all coalescing to cause a stagnant economic growth profile characterized by almost insurmountable poverty and inequalities, growing civil unrest, and impatience at what seems to be a slow pace of economic and political reform (Thompson 2001).

1.11.3 Multiple Ramifications of HIV Disease Burden Complex

The impact on communities in countries like South Africa with high numbers of PLWH will be powerful negative social and environmental forces that exacerbate individual and collective vulnerabilities in a number of ways:

1. Loss of individual well-being: PLWH have a weakened natural physiology by virtue of the chronicity and unrelenting attrition of the HIV infection as it wears down the immune system and causes accelerated aging of all structures and tissues, impaired nutrient absorption from the gut, and multiple opportunistic complications on route to a stage defined as AIDS, at which point the individual can be termed as critically unwell and without appropriate intervention will demise in a short period of time. Dramatic deterioration in well-being places a huge strain on households and causes loss of disposable income and livelihood and the tendency for conversion of personal and family assets into cash for subsistence and medical bills. This can be reversed to some extent by the initiation of antiretroviral therapy (ARV) (Bolton and Talman 2010; UNAIDS/WHO 2008; UNAIDS—AIDSinfo Country factsheets 2012).
2. Diversion of gross domestic product (GDP): Countries with high HIV prevalence have increased government spending on health infrastructure, health care providers, and ARV roll out programs, diverting already scarce funds away from other health programs and other state sectors. This places the nation as a whole in a circumstance of fiscal disadvantage and negative economic growth potential (Harrison 2010b). Funds that should be going into alleviation of poverty and attaining other national priority projects like the Millennium Development Goals (MDGs) are being diverted into keeping very sick people reasonably well.
3. Human capital: Depletion of the workforce from ill health (days off sick and death), including caregivers not being able to cope with fulltime jobs or academic activities due to responsibilities for caring for sick family members, contributes to a drain on human capital resource as a national asset and further plunges the family as a unit in deeper states of poverty (Cohen 2002).
4. Collective poverty and migration: Cumulative loss of livelihood and increasing household vulnerability to hunger, loss of assets, and entitlements encourage rural urban migration in search of means of survival and funds to remit back to support family members left in the rural setting, who engage in subsistence farming in increasingly harsh environments. This places added strain on urban informal settlements in particular and all the attended consequences of this trend (Niehof et al. 2010).
5. Dependency on free ecosystem services: As poverty sets in and survival options diminish, households resort to the consumption and utilization of the 'free' natural products derived from the biodiversity habitats in their localities. These are in the form of fuel, food, and medicinal products for personal consumption and/or are traded in exchange for cash or barter (Bolton and Talman 2010; Shackleton and Shackleton 2011).

The consequences of all these have far-reaching ramifications, affecting entire households as the morbidity and mortality from HIV and TB mainly affect the young productive sector of society. In the setting of high prevalence of undernutrition, a superimposing HIV epidemic gives rise to a vicious cycle of food insecurity and worsening health status (Mason et al.; UNEP UNAIDS 2008; UNDP South Africa 2003). There are well-established studies over the decades that prove the chronic impoverishing effects of HIV on communities in Africa, altering livelihoods and spiraling whole communities into deeper poverty traps (Cohen 2002; Niehof et al. 2010; Aliber 2003). Composition and dynamics of families are also drastically affected with more granny-headed or, at the other extreme, orphan-headed households, with high dependency on handouts from relatives and state bursaries (Aliber 2003). The HIV burden of disease complex is a key factor determining human vulnerability and resilience to other shocks and stressors that communities may be exposed to (Shackleton and Shackleton 2011; Gallopin 2006). Elucidating and standardizing the concepts of vulnerability and all its synonyms and antonyms as a science has emerged as a serious and growing area of intellectual enquiry among social scientists, politicians, and environmentalists in light of the Intergovernmental Panel on Climate Change (IPCC), which advocates that anthropogenic-induced environmental changes are going to have serious and far-reaching effects into the next century. The IPCC has stated with claimed confidence in the fourth Assessment Report (Intergovernment Panel on Climate Change 2007) that climatic change is predicted to continue along the lines of the observed trends, with increasing frequencies of both acute catastrophic and insidious events on a global scale. These predictions are made on large-scale geographical dimensions without cognizance of multiple vulnerabilities or coping capacities that exist at the grass roots level that may mitigate or amplify these hazards (Pielke et al. 2011). This is called the top-down approach. Recently, the need to introduce a paradigm shift to incorporate a parallel bottom-up approach has been gaining momentum. This approach proposes to assess the dynamics and interrelatedness of the vulnerabilities, sensitivities, resiliencies, and adaptive capacities that exist at the community level that will determine the cumulative impact, should an external climatic event or other exposure, stressor, shock, or perturbation take place. This approach attempts to identify the coping thresholds and resources of a community beyond which its adaptive and transforming capacity may fail. Furthermore, it also takes into consideration both the human (social) and ecosystems (biophysical) vulnerability coefficients when ascribing risk, of both the acute and chronic changes that may occur (Pielke et al. 2011; Vincent 2004). This chapter will adapt this philosophy in understanding the existing status of individuals and communities in light of one of the major threats to human health and resilience, which is the multiple ramifications of HIV (Niehof et al. 2010) and indirectly the impact that PLWH have on their biophysical environment in South Africa (Shackleton and Shackleton 2011).

Of particular concern for much of the subregion that is mostly dependent on rain-fed and subsistence agriculture is the sociodynamic effect and adaptive capacity to extreme or variable weather patterns such as unpredictable precipitation and warming. This is compounding an already precarious state of food security and worsening the existing state of prevailing undernutrition status of a large sector of the society (Bryan et al. 2009; McGarry and Shackleton 2009).

Such events will aggravate environmental degradation and likely trigger farming techniques and, as in the case of the effect of HIV, increased utilization and dependency on wild and natural resources from their immediate ecohabitats and environments, accelerating biodiversity loss and disturbance of the complexities of ecosystem that ensures Nature's resilience (Shackleton and Shackleton 2011; Scholes and Biggs 2004; Hunter et al. 2007).

1.11.4 Concepts of Vulnerability in the Context of HIV and Climate

The relationship between man and environment is without doubt taking center stage because of the burgeoning population and human footprint. Alongside this are a litany of concepts that define how human systems will deal with climatic perturbations and what the constitutive factors are that define vulnerability and resilience (Scholes and Biggs 2004; Daily and Ehrlich 1995b; Folke 2006).

A healthy socioecological system (SES) is understood as a system that includes the complexity of societal (human) and ecological (biophysical) subsystems in multiple dynamic symbiotic interactions, feedback loops, and interdependencies (Gallopin 2006; Daily and Ehrlich 1995b; Folke 2006). The biophysical can be further divided into the living ecosystem and the physical or the geophysical structure or matrix that houses such a system (Guillaumont and Simonet 2011b). The SES can be examined at several hierarchal levels, ranging from simple microhabitats and progressing to communities, biomes, and ultimately the global system comprising the whole of mankind (anthroposhere interacting with the ecosphere), which form the earth system as we know it (Gallopin 2006).

Human actions are clearly playing an increasingly central role in the inability of the ecosystems to perpetually continue to generate services without which humanity may ultimately cease to exist (Folke 2006). Human governance now more than ever is required to adopt a key leadership role in participating in the environment milieu in such a manner that we must perceive ourselves to be integral rather than external to the healthy functioning of the services that ensure our well-being (Ehrlich and Ehrlich 1992).

With increasing human environmental footprint, greenhouse gases and the ramifications thereof, many attempts are being expounded on how to measure indices of vulnerability, especially in the historically disadvantaged regions of the world that are expected to bear the added brunt of global climate change and variability (Bryan et al. 2009). Understanding how such communities will respond and evolve, especially as the same regions tend to carry a disproportionate share of global stressors in the form of high disease burdens, nontransparent governance, food insecurity, land degradation, and changing market forces, is critical to global justice and social capital.

Consideration of the SES as an indivisible entity emphasizes the integral relationship between modern man's ecological footprint and nature, and any attempts to disaggregate these social and ecological systems would be profoundly flawed. The envisaged 'Adaptation or Green Fund' proposed by the parties to the Kyoto protocol under the United Nations (UN) framework Convention for Climate Change (IPCC), conceived to compensate developing countries for the mitigation expenses and cost of impact, requires some form of objective rational for distribution of the funds equitably and according to vulnerability. In this light, some methods are being proposed to distinguish social and human vulnerabilities from geophysical vulnerabilities of the SES. It is envisaged that such distinction is only necessary to address the complexity and methodology by which these funds can be prioritized and equitably distributed to the most climatically geosensitive countries as a separate entity from the funding earmarked for human development objectives such as the MDGs, which are principally designated for poverty alleviation, the origins of which are deemed to be distinct from climatic perturbation. The logic behind this distinction is based on the fact that the emissions of greenhouse gases are predominantly and historically generated by the industrialized countries and are separate from the exploitative forces that have contributed to the impoverishment of Africa. This distinction, although artificial, has several potential attributes but should be viewed only in the context of the means to which it is being prescribed and not by any stretch of the imagination a suggestion that the social and biophysical entities of an SES are conceivably separable or could function independently of one another or that the genesis of poverty or climatic aberration and environmental desecration can be demarked into clear and distinct precipitating siloes (Guillaumont and Simonet 2011a,b; Ehrlich and Ehrlich 1992; Davies and Krebs 1993; Davies et al. 2011; Daily and Ehrlich 1995a).

The degree to which the SES is affected by exposure to acute or insidious effects from climate variability and possible longer term change in the setting of a high HIV prevalence within the social component of the system requires careful unraveling of complex linkages. In this scenario, climate poses external threat, while HIV pathology and its consequences undermine the SES internally.

The inherent ability of an SES to adjust and respond, also known as its adaptive capacity or resilience, ultimately defines its transforming capacity (Brooks 2003). Such relationships are complex and have multiple inherent components dictated by social and economic dimensions with factors entrenched in cohesive human existence, grass roots, and central governance (Pettengell 2010).

Sensitivity refers to the inherent capacity to preserve and resist change to the behavior and structure of an SES in the face of external or internal perturbation. The degree of sensitivity will determine the impact outcome, while resilience refers to the capacity to recover, which may be short term and referred to as coping or survival, while longer term resilience would have inherent components of adaptation. Transformation may occur in the process of adaptive resilience whereby recovery is associated with beneficial change that may improve the overall sensitivity of the system to further perturbation in the future. Crises of this nature then become windows of opportunity for improvement and positive change usually incorporating aspects of social learning and evolution. Alternatively, the sensitivity may be too high and the resilience too low to withstand the hazard, and change may become permanent and irreversible with collapse of that SES (Gallopin 2006; Ehrlich and Ehrlich 1992; Adger 2001; Intergovernment Panel on Climate Change 2007; Reed et al. 2010).

Depending on the magnitude of the assault and length of the exposure, transformations may take place in subsections of an SES or may result in radical changes in the entire structure and behavior. Vulnerability can thus be defined as the sum total of the functional component attributes of the SES, which are sensitivity; capacity to respond, cope, or survive; and transformation adaptability and inherent social learning (Gallopin 2006; Vincent 2004). Social scientists try to express this in terms of a quantifiable social vulnerability index or SVI of a society, which inherently includes the economic vulnerability index (EVI) developed by the United Nations to identify least developed countries (United Nations Committee for Development Policy (UN CDP), http://www.un.org/en/development/desa/policy/cdp/ldc/ldc_criteria.shtml). This index takes into consideration the ability of the composite SES to anticipate, resist, cope with, and respond to hazards; that the society represents not just the individuals but also the economic, political, and social institutions that govern; and the integrity of the ecological state of the environment (Vincent 2004). In this context, social vulnerability is the sensitivity of the human environment, while biophysical vulnerability is the sensitivity of the natural environment to exposures. The degree of the cumulative effect will be determined by the magnitude of these two compounding coefficients, where, for instance, the SVI of a community will be particularly high when the human population that is exposed is historically disenfranchised, of low social status with poor health status, and the environment in which they reside is ecologically delicate or marginalized. These factors have been clearly articulated in the AR4 Working Group (WG) I, where widespread poverty, ill health, educational and institutional health deficiencies, slow acquisition of technology-driven economies, war, conflict, and government ineptitude all coalesce to form high vulnerability to unpredictable and destructive weather patterns. In such instances, even small weather phenomena can result in major catastrophe and human suffering.

When considering climatic aberrations, insidious changes irrespective of the SVI may allow shocks to be absorbed slowly and entertain a relative amount of adaptability, but eventually the coping capacity threshold will be reached and the state of the SES may undergo irreversible change. However, inclement weather events such as hurricanes, typhoons, tornadoes, flash flooding, and heat waves or cold snaps may give little time for response. Without the rapid response advance warning systems in place, which is an example of social learning adaptive transformation, impacts can be large in magnitude (Midgley et al. 2010; Davies et al. 2011; Brooks 2003; Moore 2004).

In defining the primary health care philosophy, the WHO in its Alma Ata Declaration of 1978 outlined health as not just the absence of disease or infirmity but a state of complete physical, mental, and social well-being. In the context of the huge burdens of disease that plague sub-Saharan Africa, in particular, HIV, TB, malaria, and malnutrition, wellness is relative, and large sectors of society have varying degrees of absence of disease or mental well-being. In addition, Southern Africa and to some extent much of sub-Saharan Africa is known to have a disproportionate number of economies in climate-sensitive geographical locations that are dependent on subsistence farming and devoid of water containment or food storage technologies, creating regional seasonal instabilities and forcing human movement. Almost one-third of Africa including much of Southern Africa is drought prone, and as populations increase the potential to exacerbate water stress is real (Midgley et al. 2008; Guillaumont and Simonet 2011a). This threat is significant even if there would be no long-term changes in the regional climate (Vörösmarty 2000).

Vulnerability in the African setting is a function of economic status, degree of marginalization, degree of physical freedom from multiple diseases and stress, the integrity of the physical environment, as well as the institutional structures, capacity, and the legislative policies that define the collective well-being of the society. Endowments of these institutional capacities are economically, politically, and technologically driven and are collective assets and social infrastructures that are the key components of the UNDP human development index (HDI). The HDI is a surrogate measure of the standard of living and quality of life in which health and longevity are critical components.

Within the human or social aspect of the SVI, there are numerous health perspectives to consider, such as the fragility of the individuals and their social networks; the ability of health care institutions to secure the well-being of its population before, during, and after shocks; and the health care and environmental policies that are in place to define the quality or the degree of wellness of the collective and the ecological integrity of the habitat in which the individuals live and derive benefit from natures free services (Shackleton and Shackleton 2011; Intergovernment Panel on Climate Change 2007).

Vulnerable populations are susceptible to inclement weather and inevitably suffer acute or chronic impacts especially if they reside in marginalized natural habitats.

Deepening poverty ensues with loss of livelihoods, which result in further loss of capacity to cope. Individual health status will deteriorate, and options for adaptations will be minimized. Where this occurs in rural communities, this would trigger population drift and urban migration, which are strongly associated with rates of HIV transmission (Voeten et al. 2010; Deane et al. 2010). War, drought, and other refugee-driven migration further compounds vulnerabilities in the urban setting, applying more pressure on the already stretched resources in ecologically fragile high-density informal settlements. Mental health is also challenged, as many of these migrants would have left behind social networks that may soften the impact of the adversities that they are likely to encounter in their new but harsh environments for which they have had little preparedness (Vincent 2004; Adger 2001; Coffee et al. 2005).

Key elements of social vulnerability are also contingent on social dependency and demographic structure of a community. Attributes of dependency are directly related to many of the indicators of the HDI, which refer to standards of living. The overall health of the population and the number of adults in gainful employment, free from reliance on welfare grants or bursaries, are indicators of a resilient society. Demographic structure is based on gender and age distribution and the complexity of the immediate social network. A community may have a normal or skewed distribution based on the forces that determine reproductive rate, good health, and longevity.

The current figures for national employment reveal that 35% of South Africa's employable population aged between 15 and 49 are without work, creating a huge sector of society highly dependable on national and social grants. The Government of South Africa is about to pass a new bill to introduce wage subsidies for unemployed youth aimed at creating opportunities for developing the skills of the 15- to 29-year old sector of society that has the worst unemployment rates. This is primarily aimed at retarding a growing security risk and social unrest that will ensue if the situation persists (National Treasury 2011; http://www.treasury.gov.za/documents/national%20budget/2011/Confronting%20youth%20unemployment%20-%20Policy%20options.pdf).

Incidentally this same age group has the highest HIV prevalence of about 16% (Dorrington et al. 2006). This produces reduced life expectancy and a skewed population composition and structure of mainly young people below the age of 15, with a weak or dying unproductive middle-aged group and a declining adult and aging population. This demography is not conducive or able to support a robust local and national economic growth projectile (Harrison 2010b; Intergovernment Panel on Climate Change 2007; Pachauri and Reisinger 2007). This is the reverse of developed countries where there is the cumulative aggregate of human capital with advancing age and expertise is retained in society, with huge returns for investment in lifetime skills and capacity development (Dorrington et al. 2006). This abnormal demographic composition caused by the HIV epidemic and unemployment promotes population vulnerability on many fronts and weakens household and institutional capacities, as national and household reserves and resources are diminished and what exists is diverted to the caring and maintenance of the sick and weak.

1.11.5 Origin of HIV and Its Propagation in Context of Changing Human Demographics and Environmental Vulnerabilities

At the advent of the agricultural era, critical masses of humans converged into stable communities in close proximity to domesticated animals, which permitted the cross-species zoonotic emergence of new human pathogens such as the flu from avian flu, small pox from monkey pox, and measles from rinderpest. Humans and animals share about 300 diseases, and 55% of human diseases are of animal origin. Most of man's worst infectious killer diseases such as TB, measles, cholera, influenza, malaria, and most recently HIV have originated from the animal kingdom that we have become closely associated with by virtue of changing human ecological interactions (Daily and Ehrlich 1995b; Gommes et al. 2004; Weiss 2001). These diseases have a short acute infective period and thus allowed the persistence of these infectious agents in the communities where humans exist in close proximity to one another (Black 1975). Such viruses that cause acute infections also appear to achieve greater heights of virulence when contracted from familiar members with similar genetic composition (Black 1992). HIV, which is directly related to the simian immunodeficiency virus (SIV), is another classic case of a viral opportunistic event that has emerged as a devastating human pathogen in a very rapid time frame of less than 50 years during a period spanning the colonial era in Africa. Severe disruptions of normal human ecological interactions and an unethical health care milieu created extreme susceptibility of indigenous Africans to a series of simian (monkey) to human cross-species events in the Congo River Basin, giving rise to the evolution of the HIV-1 virus subtype, the direct descendant of the SIVcpz, whose natural host is the chimpanzee (Moore 2004; Pepin 2011). Under normal conditions, humans are not particularly susceptible to SIV infections, but when conditions were right the virus gained access in severely stressed and immunologically suppressed humans and was subsequently able to evolve virulence and adapt as a new human pathogen capable of human-to-human transmission (Weiss 2001). Subsequently, a multitude of other demographic, trading, leisure, and mobility cofactors caused the rapid dissemination of the virus across the globe (Pepin 2011).

There are now at least 20 megacities with population sizes in excess of 10 million inhabitants worldwide and the number is set to rise. The twentieth century witnessed the rapid urbanization of the world's population. The global proportion of urban population increased from a mere 13% in 1900 to 29% in 1950 and, according to the 2005 revision of World Urbanization Prospects, reached 49% in 2005. Since the world is projected to continue to urbanize, 60% of the global population is expected to live in cities by 2030. These are unprecedented trends, and according to the latest United Nations population projections, 4.9 billion people are expected to be urban dwellers in 2030 (Midgley et al. 2010). In the past few decades, the human head count within the earth SES has reached 7 billion, which is the densest ratio of humanity to ecological systems that has ever been (Daily and Ehrlich 1995b). It comprises a large population of compromised individuals who live in mega overcrowded and polluted cities with poor nutrition and sanitation, creating the ideal circumstances for opportunistic infections and the evolution of virulence due to high transmission capacity (Moore 2004; Gommes et al. 2004; Weiss 2011; Marx et al. 2001).

In addition, large cities have the advantage of creating a sense of anonymity, which provides the freedom to act without the normal inhibitory mechanisms of a regulated society, promoting sexual freedom, prostitution, violence, and drug use, which are some of the main prerequisite conditions ideal for the transmission of HIV (Coffee et al. 2005). Movement of large populations of people can create disturbances in ecohabitats and balanced food chains, liberating certain populations of flora and fauna to expand uninhibited by the elimination of their natural predators. This has the potential for creating reservoirs for vectors of human disease and zoonotic potential in an increasingly immunocompromised population (Davies and Krebs 1993; Stiling 2001). The impact of human modernization and population dynamics giving rise to stress is almost certainly overlooked in the whole scheme of things. It is becoming clearer that stress in itself is a strong predisposing factor, increasing the susceptibility of humans and the animals they interact with to multiple infections. There are multiple causes of increased stress such as ambient temperature (too hot or too cold), inclement weather patterns, crowding, space confinement and poor ventilation, transportation issues, lack of economic empowerment, and the emotions associated with social defeat. These lead to a state of permanent metabolic alert characterized by insomnia and increased plasma cortisol and adrenalin, which are the fight and flight hormones. The physiologic and psychological stress and hassles of everyday life events in poor crowded living environments, lack of social support, and social family networks all diminish the robustness of the immune system and increase vulnerability and susceptibility of individuals to acute infections and reactivation of latent infections (Brogden 2002; Agarwal and Marshall 2001; Avitsur et al. 2009; Rozlog et al. 1999; Holloway et al. 2010; Walensky et al. 2008; Harrison 2010b).

1.11.6 Characteristics of the Key Preconditions Contributing to Current Vulnerabilities in South Africa, Status and Trends

1.11.6.1 HIV/AIDS

HIV is now the largest health burden confronting South Africans and threatens to wipe out the economic, social, and developmental gains achieved in the past century (Harrison 2010b). It is now consuming a large proportion of the health budget in South Africa, with attempts to roll out and implement the largest ARV program globally to support the estimated 5.5 million people living with HIV/AIDS. The HIV epidemic has reduced life expectancy from 52 years in 1997 to 43 years in 2007 (UNDP South Africa 2003). There should be an estimated 2.75 million people on ARV treatment by 2012 if recruitment onto treatment programs is effective (Dorrington et al. 2006; Walensky et al. 2008; Harrison 2010b).

1.11.6.2 Pathophysiology of HIV/AIDS

The adaptive immune system of humans comprises billions of white blood cells known as CD4 helper and CD8 killer lymphocytes, which represent a huge repertoire of protein recognition sites on their cell surfaces, whose specificity enables them to recognize and target with high specificity any possible foreign pathogen. Recognition by these cells of a pathogen that has gained access into a human system is followed by activation of a dramatic complex of cascading rapid response elements, CD4 and CD8 cell replication, and recruiting of other cellular components of the immune system in what is known as the cell-mediated inflammatory response.

The outcome of this inflammatory burst of activity is the elimination or containment of the invading pathogen. This highly specific pattern recognition function is stored and fine-tuned in the genetic program of each of the CD4 cells, which once exposed to a pathogen initiates the inflammatory response and will be subsequently retained as antigenic experience and designated as CD4 memory cells. As a result of this memory, subsequent exposure to the same pathogen will result in an exponentially faster and more specific response coordinated by the memory CD4 and CD8 cells, culminating in rapid clearance of the infection and generally not permitting full manifestation of the pathological consequences of that infective agent. These are the attributes of immunity that are exploited by vaccination technology. The CD4 cells are a major component of this adaptive immune system that orchestrate this highly specific immunological reaction of an individual aimed at eliminating foreign antigens or pathogens by focusing the CD8 cells, which then deliver their specific death signals to invading pathogens. The irony of HIV infection is that the target cell of choice for viral replication is the CD4 cell. This results in death and paralysis of billions of the ‘field marshal commanders’ of the immune system, resulting in a chaotic, disorganized, and depleted army of immune cells devoid of precision and coordination. This is the reason HIV is such a formidable pathogen and able to induce such profound immunological paralysis (Sompayrac 2012).

Following an exposure to the HIV (sex, needle stick, blood, or transplacental), a susceptible individual will manifest features of the primary infection, which are similar to symptoms of a flulike illness. Within a short period probably lasting a few weeks, the virus will devastate the immune system of the host by depleting majority of the memory CD4 cells that line the mucosal surfaces of the gut, lung, and genitourinary systems. This memory cell repertoire has taken the lifetime of the individual to develop and acquire and is almost virtually wiped out in a matter of a few weeks. This places the immune system in a state of near collapse and disarray and leaves the mucosal surfaces like the lining of the gut that should have a profound level of ‘CD4 memory’ immune surveillance and protection almost bare from an immunological perspective. This is described as the ‘leaky gut syndrome’ and is associated with loss of gut integrity, vulnerability to the translocation of large quantities of microbes from the gut into the blood stream, as well as degrees of malabsorption of vital nutrients. (Brenchley et al. 2004; Chang and Qin-xue 2009; Brenchley and Douek 2008; Downs 2010).

The immune system is able to partially and temporarily bring under control this acute devastation of immunological memory, and the infection transitions into a chronic phase, which may last from a few years to over a decade depending on the genetic makeup of the individual and environmental factors. In this time frame, the partially crippled immune system is unable to clear the HIV virus and is extremely vulnerable to microbe opportunistic infections and reactivation of latent pathogens like TB (CDC

Factsheets www.cdc.gov/hiv, Cancer in HIV IARCR, Cancers-Disease and Mortality in sub-Saharan Africa NCBI www.ncbi.nih.gov). Some of these opportunistic infections are notorious cancer-inducing viruses that the body is unable to eliminate swiftly and therefore predisposes to potential for cancer formation. The attrition rate of the CD4 cells is relentless nonetheless as the semiparalyzed immune system tries to recover under this persistent influx of pathogens from the gut and other mucosal surfaces and opportunistic infections. This complex sequence of events is responsible for keeping the body in a state of chronic immune activation (Ostrowski 2010). Eventually the disorganized immune system burns out and exhausts itself in this milieu of uncompensated activation and oxidative stress and then finally collapses as both the CD4 and CD8 cells decline dramatically in quantity and quality with the advent of several clinical conditions attributable to failed immunity. These conditions are typically characterized by TB reactivation, unusual opportunistic infections with fungal and parasite microbes, certain cancers such as lymphoma, Kaposi, and cervical cancer (Abayomi et al. 2011; Mantina et al. 2010; Wiggill et al. 2011). At this stage, when these events start to manifest, coupled with evidence of depleted CD4 cells in the blood which is determined by the 'CD4 count' blood test, the stage of the HIV infection is described as progressing into a state of acquired immune deficiency syndrome or AIDS. These events are also described as AIDS defining (Abayomi and Landis 2008; Abayomi et al. 2008).

Certain coexisting conditions predispose and increase the risk of acquiring HIV infection in the first instance and promote accelerated transition to the stage of AIDS after infection takes place. These are the presence of other simultaneous infections such as sexually transmitted disease; tropical diseases such as malaria, TB, tropical enteritis, and schistosomiasis; psychological stress; and protein–energy malnutrition, a state that is aggravated by the impact of the virus on the gut as described earlier (Bolton and Talman 2010; Anema et al. 2009).

South Africa is home to the world's largest population of young PLWH and has to date resulted in the deaths of at least 2.6 million South Africans, mostly children and young adults (Harrison 2010b; Avert 2010). Over 250 000 South Africans died of AIDS in 2008 (Harrison 2010a). HIV/AIDS accounted for about 75% of premature deaths in South Africa in 2010, up from 39% a decade ago (Bradshaw and Dorrington 2007). There are probably close to two million AIDS orphans rising in South Africa (UNEP UNAIDS 2008). Almost one-third of women aged 25–29 and over a quarter of men aged 30–34 are living with HIV (Harrison 2010b).

In response to the massive anti-HIV National Strategic Plan (NSP) under the South African National AIDS Council (SANAC), the HIV prevalence among people older than two has peaked and stabilized at about 11% and is likely to remain there for at least 5 years (Avert 2010; Scott and Harrison 2009). Women show a sustained rise from 5% in the late teens, reaching a peak of above 30% by 29 years of age and subsequently reverting to about 5% in 55–59 year olds. In men, the prevalence starts later at 5% in 20–24 year olds, reaching peak levels of 25% in 30–34 year olds. There are indications of significant declines among young people. Child mortality has probably also peaked and should decline further with increasing availability of treatment. The decline in prevalence in younger age groups is linked to better access to prevention of mother-to-child transmission and much higher self-reported condom use. The number of PLWH who now need to be recruited into the expanded antiretroviral program is estimated to be 2.25 million, increasing to 2.75 million by the end of 2012 (Walensky et al. 2008). People living in informal settlements have the highest rates of HIV infection (~20% in the urban informal compared to ~10% in rural-formal, informal, and urban-formal settings). Fragmentation of urban-transition, rural/urban, and regional migration patterns for economic or climatic reasons creates the conditions and vulnerabilities that fuel the spread of HIV (Harrison 2010b). Future trends suggest that the incidence of new cases will continue to fall, but the ARV program will maintain prevalence as PLWH will be set to live longer. Some coping mechanisms identified during environmental stresses like drought and floods are environmental desecration, migration, prostitution, and dispatching children away to relatives in distant locations. The continuous growth of large populations in crowded high-density and informal settlements with poor amenities has been identified to be hot spots for continued transmission that will facilitate new infections of HIV and TB. (McMichael 2008; Gommes et al. 2004; Holloway et al. 2010).

1.11.6.3 Tuberculosis (TB)

Between 6 and 10 million South Africans are believed to be infected with *Myobacterium tuberculosis*—a bacterium that causes TB. South Africa has one of the highest TB burdens in the world and is ranked third after Asian countries such as India and China (WHO 2010; Ndjeka 2011). TB is spread from infected persons to vulnerable persons in close proximity by airborne TB-laden droplets produced by aerosols that are generated by coughing. TB spread is facilitated by poor ventilation such as occurs in congested living conditions in shantytowns and houses or crowded public transport and by underlying lung injury. It is estimated that the small vaporized droplets of less than 2 microns produced by coughing can remain suspended for up to 4 h in a confined unventilated area. When breathed in by uninfected persons, these droplets are capable of penetrating to the smallest unit of the lungs where they multiply, creating the highest chance of causing active disease in human beings and particularly if factors in the community promote reduced immunity.

Exposure to TB in adults results in various clinical pictures. Some patients eradicate the bacteria completely with no immunodiagnostic evidence of exposure to the mycobacterium (Dheda et al. 2010). Most immune-competent persons will show immunodiagnostic evidence of exposure to the bacillus, with no clinical evidence of the disease (latent TB). In latent TB, patients do not have clinical symptoms of TB but the bacillus is present in the lungs in an immunologically controlled non-replicating state with a probability of progressing to active TB at any time in their lifetime when immune containment is weakened. Persons with a compromised immune system due to HIV, malnourishment, or stress are most likely to develop active TB at first exposure or reactivate latent disease (Dheda et al. 2010). Only a small fraction of normal and immune competent persons exposed to TB will develop active TB in their lifetime, estimated at about 12%, which is usually confined to the lungs or less frequently in a disseminated state affecting multiple organs and systems.

Widespread or disseminated TB results from hematogenous spread of mycobacteria from the lung to many organs (Grewal 2012; Schaaf et al. 2009). Common sites of spread include the bone marrow, lymph nodes, liver, spleen, brain, heart, and the skeletal, gastrointestinal, and genitourinary systems. Disseminated TB is associated with weakened immunity and is observed in children less than 3 years of age, elderly patients, and patients who are immunocompromised such as PLWH. In endemic areas, disseminated TB contributes significantly toward disease morbidity and mortality, particularly in countries with a high HIV infection prevalence (Reuter H et al. 2005). In children, the risk of developing active TB is higher while disseminated TB is seen more in children less than one year of age (Eamranond and Jaramillo 2001). Trends now reveal extremely worrying data indicating that drug-resistant TB (DR-TB) is on the increase in South Africa. DR-TB comprises collectively multidrug-resistant TB (MDR-TB) and XDR-TB. Six percent of re-treated TB cases and 1% of new cases are multidrug -resistant (MDR-TB), which translates to over 9000 cases in 2009, and a cumulative total of 45 000 MDR-TB cases have been diagnosed in South Africa between 2004 and 2010. (WHO 2010; Coetzee and Kroonhof 2006; Gandi et al. 2006; Becerra et al. 2010; Migliori et al. 2010).

1.11.6.4 Relationship between TB and HIV

As a result of the high background HIV prevalence in the society and poor overcrowded living conditions, TB is going through an unprecedented resurgence in South Africa (Harrison 2010).

The spread of the TB epidemic is closely related to the HIV epidemic, particularly in sub-Saharan Africa, which has the highest HIV prevalence rates in the world. In the setting of HIV, the risk of activating latent disease is increased by 10% per annum (Sudre et al. 1992). As indicated earlier, the incidence of TB in South Africa rose from 301 in 1990 to 971 per 100 000 people in 2009, representing a tripling of new cases in the past 20 years, which coincides with the growth of the HIV epidemic (Middelkoop et al. 2009). Of all the new TB patients, 58% were also infected with HIV (WHO 2010). The mortality rates in 2008 due to TB were reported as 153 per 100 000 people of which 66% were due to coinfection with HIV (Harrison 2010a). Unfortunately, there is no reliable data available for the incidence of TB in children in many African countries, including South Africa. Pediatric studies in South Africa have shown that TB is present in more than 40% of children infected with HIV. Children living with HIV have an unprecedented 24-fold increased risk of developing TB during their first year of life than children without HIV (Hesseling et al. 2009). The incidence of smear-positive TB has increased by between 200 and 300 new cases per 100 000 population annually in the presence of HIV. This does not take into account the numerous smear-negative patients who form a significant number of HIV-positive coinfected cases. It is in this setting that drug-resistant TB is set to become a major health issue (Ndjeka 2011).

1.11.6.5 Reciprocal Relationship between Food Security and HIV Complex Burden of Disease

The International Food Policy Research Institute (IFPRI) estimated that a minimum of 1800 kcal day^{-1} is required for most people to live a normal productive life (IFRI GHI 2011). The term undernutrition is defined by the IFPRI as deficiencies in energy, protein, essential vitamins, and minerals and may arise from inadequate intake or poor utilization due to illness and infection or combinations and will be referred to as protein energy malnutrition (PEM). PLWH have increased nutritional requirements in the form of an additional requirement of 400 kcal day^{-1} of energy and about 50–100% more of protein (East, Central, and Southern African Health Community (ECSA-HC), Food and Nutrition 2008; Mwadime et al. 2003). In the setting of coinfection with TB, these requirements are even higher (Macallan 1999). This fact is supported by the findings that demonstrate in low-resource areas where nutritive food assistance supplementation given to PLWH resulted in both weight gain and retardation of disease progression particularly for those not on ARV or at advanced stages of the disease (Rawat et al. 2010).

In the three decades preceding the turn of the century, 65% of persons living in sub-Saharan Africa were judged to be living in absolute poverty and undernourished (Chambers 1995, 1997). This ironically coincides with the emergence of the rapid escalation of the HIV epidemic in the region. The Food and Agriculture Organization (FAO) has released dramatic statistics estimating the magnitude of PEM in the subregion of southern Africa. Estimates of the order of 95 million people are believed to be living under the threshold calorie intake for normal healthy nutritional status, and the trend in the past decade is deteriorating (Confalonieri et al. 2007; De Wit 2010). Data on the global hunger index (GHI) released in 2011 by IFPRI shows that sub-Saharan Africa has one of the worst hunger index scores worldwide, with many of the southern Africa regional countries in the severe to alarming scales of the GHI. In South Africa, malnutrition rates have deteriorated in the past decade. Recent findings indicate that one in five children are stunted and one-third of women and children were anemic, while two-thirds of children have vitamin A deficiency and almost a half were iodine deficient (Gasa 2009). This publication states that there are an estimated 14 million people who are food insecure and 1.5 million children who suffer from PEM in South Africa and goes on to elucidate the main reasons for this concerning data. The main factors responsible for this are massive unemployment rates of between 35 and 40% nationwide, and South Africa ranks third on the global list of most unequal economies, with the largest gaps between the rich and the poor. The government's attempts to eradicate extreme poverty has seen the social assistant grants rising from Rand 10 billion (∼US$1.3bn) in 1994 to Rand 40 billion (∼US$6.0bn) in 2004 and still rising with the number of beneficiaries quadrupling. In some provinces of South Africa unemployment is as high as 93%, and nationally 55% of the working population had monthly incomes of between 1 and 1000 South African Rand, the equivalent of 10 cents and $140 USD. Despite interventions there are hot spots that are poverty nodes in rural and urban sectors caused by increasing unemployment, rising food prices, HIV/AIDS, adverse environmental and climatic conditions leading to declining crop and livestock production attributable to increasing heat, decreasing moisture, and unpredictable growing seasons. In some cases, excessive precipitation can also result in both crop failure and dramatic livestock losses. A recent survey in South Africa by the

Health Science Research Council (HSRC) analyzing the nutrient and balanced dietary intake index (dietary diverse score (DDS)) as an indicator of adequate nutrient intake found that 40% of all South Africans had inadequate intake of nutrients, and this ranged from 15% in some provinces to as high as 62% in the worst affected areas. When dissected per type of location, rural and urban informal settlement had the worst profiles with greater than 50% evidence of PEM based on intake as compared to 26% in urban formal locations (Human Science Research Council 2011).

PEM lowers immunity and predisposes people to infection. Evidence now clearly demonstrates that any person with an infection has a significantly higher protein and calorie requirement. Populations with a high prevalence of PEM (as in Southern Africa) are more prone to be infected by the multiplicity of tropical infectious diseases in the environment (Chatraw et al. 2008; de Waal and Whiteside 2003). Furthermore, infection in this setting of PEM compounds the situation and causes further deterioration of the existing nutritional status, ushering in a vicious cycle of worsening nutritional deficit, fading immune status, and super or multiple coexisting infections or even death (Macallan 2009). The combined effect of PEM and infection is profoundly synergistic and lead to metabolic effects that cannot be rectified by antimicrobial treatment alone and must incorporate nutrient replacement strategies for maximal effect (Chatraw et al. 2008; Fawzi et al. 2007a,b). Children are particularly prone to the effects of PEM because it causes developmental retardation or involution of the thymus gland. The thymus gland is central and critical to the orchestration of an effective immune system, as the CD4 and CD8 cells are nurtured and developed in this organ. These are the immune cells that would be responsible for resisting the invasion of the body by an HIV virus. Furthermore, infection in childhood requires higher supplementation with protein and calories when compared to adults (Keusch and Medlin 2003).

These trends demonstrate the profound relationship between the environment, food security, and the infection profile of a community and region. The evidence is that sub-Saharan Africa, which has the world's highest burden of infectious disease, is the only region showing a growing proportion of undernourished populations predisposed to infection and death. This can be attributed to many sociopolitical factors, but certainly there are records of historical abnormal weather patterns as far back as the post-Second World War era that have influenced food security in the whole region (Ambrus and Ambrus 2004a,b). Specifically and in the context of HIV and PLWH, PEM is responsible for lower CD4 counts and higher viral load indicative of poorer control of viral replication. PLWH who are food insecure are less likely to start ARV or maintain the necessary adherence of >90% to achieve the required viral suppression associated with longevity and improved prognosis. PEM is associated with a compromised ability to suppress the virus to undetectable levels, which is the desired gold standard of effective treatment in patients on ARV therapy. Therefore, the preexistence and concomitant presence of PEM renders treatment less effective (Weiser et al. 2009; Wang 2011).

Risk of horizontal and vertical transmission is increased in PEM because of higher viral burden, lower immune and mucosal protection, and the tendency to engaging in risky behavior such as transactional sex out of the need to alleviate food deprivation. Undernutrition facilitates the acquisition and spread of HIV infection in the first instance and at the same time aggravates the resulting chronic HIV burden of disease. The resulting physical incapacitation and loss of well-being leads to further deterioration of food security (Anema et al. 2009). This complex is referred to as the new variant famine (NVF) in Southern Africa. In normal circumstances, populations employ a variety of coping and adaptive mechanisms to get through and survive shocks such as crop failure by redirecting savings or disposing of assets for a brief period till the shock is overcome and normalcy is reestablished. In populations with medium to high prevalence of HIV, recovery is impaired by those infected and affected by the disease, and as a result households and communities are likely to descend into poverty rather than ride the tide (de Waal and Whiteside 2003; Naysmith et al. 2009).

In South Africa, where food is not technically in short production, adequate nutrition is not accessible to a large sector of the society that is located either in large informal settlements or in rural locations most vulnerable to PEM because people depend on rain-fed agricultural traditional systems for subsistence. Macroeconomic reasons among other factors associated with a heterogeneously diverse economic landscape are responsible for this dichotomy (McMichael 2008; de Waal and Whiteside 2003; SADB 2008; McMichael and Butler 2009).

1.11.7 HIV-Induced Human and Environmental Vulnerabilities and Effects of Climate

A significant proportion of South Africans have serious and complex health challenges as outlined earlier, emanating from the recent political and social circumstances that characterized the colonial and apartheid eras in the histories of the subregion. These health issues were certainly compounded by forced human displacement and poor subhuman living conditions, the remnants of which are clearly visible in numerous and dense informal settlements (Holloway et al. 2010; Kilian et al. 2005). This scenario creates and constitutes a people with a unique disease complex as outlined earlier in this chapter. Underpinning these conditions are the common denominators of poverty and lack of social amenities (Midgley et al. 2008).

In the Third Assessment report of the IPCC (IPCC TAR WGII 2001), human health vulnerabilities are categorized in three tier levels:

Individual

- Disease status of population (environmental stressors increases disease status proportionately)
- Poverty (lowers resistance to health challenges)
- Demographics (percentage of susceptible: young and elderly)

Community

- Water quality and quantity
- Food supply, storage, and distribution
- Access to information and ability to galvanize response
- Local disease vector distribution and control programs

Geographical

- Extreme weather patterns peculiar to a locality
- Population living in low-lying coastal areas
- Population on the boundary of a known vector-borne disease
- Rural population may have poor access to health infrastructure
- Urban population susceptible to effects of crowding
- Extent of environmental degradation and air pollution

South Africa is a relatively dry and temperate country with an annual rainfall of about 500 mm, with most of its water obtained from surface water entrapment. Weather patterns have been observed to change in the past 50 years, with significant trends toward consistent but gradual warming and changes in temporal and spatial precipitation characterized by increase in intensity and duration per event interspersed by longer dry spells (Christy et al. 2009; Pielke et al. 2006). Temperature trends may be due to land-use change and siting issues, in addition to any changes from added CO_2 and other greenhouse gases (Christy et al. 2009). There are unresolved issues with the assessment of multidecadal global land surface temperature trends, and there are no reliable regional predictive skills (Pielke et al. 2011, 2006; Pielke 2012 blog). As most of the national water is already fully committed, any changes in climatic conditions would likely have major impacts on economic development, health, and livelihoods by directly influencing water quality for human use, food security, flooding events, loss of biodiversity, and warming with increasing episodes of heat waves and inversion days (brown haze). With specific reference to health, these changes would impact air and water quality, with increased pulmonary complications and waterborne diseases, as well as have a direct effect on human physiology during heat waves (Haines et al. 2006). Fewer but heavier flooding and increased fire events would have consequential acute direct physical damage and resultant stress (Midgley et al. 2005). In PLWH, these conditions would likely have adverse health effects because respiratory reserve is already compromised by TB and gut integrity is suboptimal with increased susceptibility to nutrient deficiency, opportunistic infections, and gastroenteritis.

1.11.7.1 Scenarios in South Africa and Possible Thresholds for PLWH

1.11.7.1.1 Heat Stress

These effects exhibit spatial and temporal variability across regions. The extremes of age groups, those with existing chronic ill health like HIV/AIDS especially, and the low socioeconomic strata are especially vulnerable (Midgley et al. 2008; South Africa's Second National Communication on Climate Change 2011; Bambrick et al. 2008). The human physiology is designed to function optimally at environmental temperatures ranging between 17 and 31 °C (McMichael 2008). When ambient temperatures exceed 34 °C, the risk of hyperthermia is high. In the absence of corrective measures, dehydration and multiorgan instability will ensue, resulting in exhaustion, ill health, and death from cardiovascular collapse within a short time frame. Data from South Africa over four decades indicate that the number of hotter days and nights are increasing, especially in the interior, while cooler days and nights are decreasing, suggesting that warming trend may possibly result in increased casualties from heat stress (South Africa's Second National Communication on Climate Change 2011). Data from Malawi suggests that even in the early stages of HIV infection, kidney function can be compromised in as many as 60% of patients from a direct effect of the virus on the kidney. The kidney is a key organ in regulating water and intravascular volume, which maintains normal blood pressure critical for vital functioning of all organs (Struik et al. 2011). Furthermore, certain ARV drugs used to treat HIV have direct kidney toxicity profiles and can in themselves lead to progressive renal failure (Daugas et al. 2005). PLWH are more prone to dehydration, especially if they are in the late stage of the disease and have other complications associated with fevers. This is particularly true of frequent gastrointestinal disturbances such as diarrhea and mouth ulcers, which predispose PLWH to dehydration and malabsorption of critical minerals, proteins, and fluid (Garcia-Prats et al. 2009).

1.11.7.1.2 Storms and Flooding

The health impacts of catastrophic and extreme weather events are well known. Disaster occurs when these climate hazards converge with a vulnerable population, resulting in severe structural damage and social disruption that can result in profound psychological impact and behavioral changes when trying to cope. Some of the main factors driving or shaping vulnerabilities are population growth and concentration in high-risk areas, compounding poverty and environmental degradation typically seen in the informal settlement areas where HIV prevalence is highest and also typically the only location that can potentially accommodate climate and economic refugees. There is great risk of environmental pollution, social dislocation, and infectious epidemics during such catastrophic events (Midgley et al. 2008; Holloway et al. 2010; South Africa's Second National Communication on Climate Change 2011).

1.11.7.1.3 Waterborne Diseases

Waterborne infectious diseases are any illnesses caused by the consumption or usage of contaminated water. These conditions have a close association with aberrant weather patterns and disaster situations (McMichael 2008). Typical PLWH are very prone to these waterborne infectious disease pathogens including bacteria, viruses, and protozoans. Waterborne infectious diseases pose an acute problem in areas where populations are expanding and water supply and sanitation infrastructure are either rudimentary or nonexistent as are typically seen in informal settlements (Thambiran 2008). The most common waterborne infectious diseases in South Africa include cholera, dysentery, typhoid, and other rotavirus infections. El Niño–Southern Oscillation (ENSO) is regarded as the strongest naturally occurring source of climate variability that directly or indirectly affects factors that influence outbreaks of these waterborne diseases and can shift the timing and duration of such on an annual basis. The links between weather and diseases are well established, as many diseases are seasonal or occur during or after unseasonal extreme events such as floods or drought (Rozlog et al. 1999). Studies provided some quantitative evidence for the link between climate and cholera outbreaks. A study was based on one of the longest available health data sets (from Bangladesh for 1893–2001), where a strong and consistent ENSO signature for the period 1980–2001 explained 70% of the excess variance of cholera at the time (Patz 2002).

Exploitable water supplies in South Africa are confined to rivers, artificial impoundments, and groundwater. The total capacity of impoundments amounts to more than 50% of South Africa's total average annual river runoff (Oberholster et al. 2005; Wilson et al. 2005). Changes in precipitation and evaporation would dramatically affect the quantity and quality of these sources of water and predispose to waterborne diseases. Africa had 94% (179 323 cases) of global cholera cases in 2008 (WHO 2009), 12 752 of which were in South Africa (Ottawa Charter for Health Promotion 1986; OCHA 2009).

South Africa is at risk of cholera and other waterborne diarrheal outbreaks because of its historical precedents of such outbreaks, proximity to neighboring countries where many of the microbes causing diarrhea are known to be endemic, the movement of people between these areas and South Africa, the number of poor and vulnerable people dependent on natural water, and environmental conditions conducive to the survival and growth of these pathogens, including hot rainy summers, droughts, estuaries, and port cities. Communities in areas with no or limited access to safe water supplies and sanitation, poor or limited health infrastructure, and unfavorable socioeconomic and environmental conditions will always be at risk of cholera and other waterborne diarrheal outbreaks. Overcrowding plays an important role in the rate of spread of these gastrointestinal pathogens (Lucas et al. 2005; Soto 2009; Collins 1996). Cholera in particular produces a dramatic depletion of intravascular volume in a short time by copious vomiting and diarrhea. PLWH are especially prone to waterborne diseases of this nature and probably have less physiological reserve than non-HIV infected persons as outlined earlier, causing faster collapse of cardiovascular systems and renal function, resulting in higher morbidity and mortality. In an outbreak of cholera in Kwazulu Natal in the year 2000, attending doctors were sometimes unable to distinguish the profound diarrheal disorders found in AIDS from that of typical cholera. In the setting of existing HIV infection, cholera is likely to cause higher morbidity and mortality especially when socioeconomic circumstances are poor and the population has a high HIV complex disease burden (http://www.bvsde.paho.org/texcom/colera/choleraNatal.pdf).

In a report from Haiti following the recent earthquake causing thousands of displaced people, a cholera outbreak that ensued was found to be most devastating among HIV-positive persons, causing rapid collapse and death in about 2–3 h compared to non-HIV infected people. (http://www.irinnews.org/Report/91152/HAITI-HIV-positive-people-especially-vulnerable-to-cholera).

1.11.7.2 Air Quality

The planetary boundary layer (PBL) is the lowest part of the atmosphere, ranging anywhere between 100 and 2000 m above the surface of the ground. Its behavior and properties are directly influenced by the topography of the earth's surface. The flow of wind in this layer is typically turbulent and responds to surface forcing such as temperature, resistance or drag, moisture, and ecological complexity. These forces are important in affecting weather patterns and the rate of exchange of particulate matter (PM) between the PBL and the free atmosphere above it (Seidel et al. 2010). Precipitation in particular acts as the main sink for suspended PM, while wind causes dispersion (Jacob and Winner 2009). Stagnant air episodes occur primarily in winter, when inversion conditions occur, trapping pollutants and increasing their concentrations within the PBL. The air pollution disappears only when the inversion is broken up by wind, rain, or the warming effect of the sun. Human-generated emissions affect air quality and subsequently human health. Exposure to air pollutants, such as PM, sulfur dioxide, ozone, and nitrogen dioxide, is associated with a depressed immune system and cardiorespiratory morbidity and mortality (Pope et al. 2002; Brook et al. 2004).

A significant air-related health effect of pollution is in relation to ozone, PM, and brown haze content of the PBL, especially in urban areas, all resulting from fossil fuels. Ozone, even at relatively low levels, when inhaled has been associated with pulmonary damage and asthma attacks (Mittal et al. 2007). The size of the PM in air suspension determines its capacity aerodynamically to be inhaled and to penetrate the lungs, either causing local damage to the lungs or being able to penetrate into the circulation. These sizes range from the largest at PM10 (10 μm) to the smallest ultrafine particles (UFPs) (0.1 μm in diameter), which result mainly from combustion processes. UFPs demonstrate very high capacity to penetrate and deposit deep in the human lungs and alveoli, potentially leading to enhanced biological toxicity. UFPs may even be able to pass directly through the lung lining into the blood, which could allow them to be disseminated systemically though the blood with profound systemic effects (Brook et al. 2004). All these factors have a detrimental effect on PLWH who have compromised lung function from frequent pneumonic episodes and pulmonary TB with residual lung fibrosis. The permeation of fine air pollutant PM through the lung lining into the blood stream causes additional oxidative stress toxicity to the blood vessel lining in the setting of high levels of existing oxidative stress generated by the chronic inflammation of HIV infection predisposing to vascular complications (Abayomi et al. 2008; Brook et al. 2004).

Indoor air pollution is also a major concern, as almost one-third of homes in South Africa rely on indoor burning of fossil fuel particularly in the homes of indigenous Africans in high-density locations and informal settlements. Limited ventilation in these homes coupled with overcrowding makes this scenario a health hazard. Indoor pollution is associated with increased risk of chronic obstructive airway disease (COAD), asthma, bronchopneumonia, and TB, especially in young children or adults with underlying lung disease, cardiovascular disease, or HIV/AIDS (Norman et al. 2007a,b). Norman et al. propose that the underlying HIV infection and PEM work synergistically with indoor pollution to increase the risk of these complications. Climatic conditions provide increased exposure risk to these conditions when climate-induced migration force crowding in informal settlements or there are episodes of cold snaps or prolonged rain-induced cold and damp (Holloway et al. 2010).

1.11.8 Adaptation

Coping mechanisms identified during environmental stresses such as drought and floods are migration of one or all members of a family, dispatching children away to relatives in distant locations, consumption of assets, exploitation of natural resources, remittance of funds from relatives, and prostitution. Dislocation of family units and transactional sex increase the risk of HIV transmission (Pettengell 2010; MIDSA 2009). Where migration results in loss of man power and brain drain from the region as a whole, it also poses even more challenges to the dearth of skills appropriate to accommodate regional economic growth, a concern that was initially addressed by the Joint Initiative Project for Skills Acquisition and more recently the New Growth Path Initiative, which has a main mandate of addressing massive joblessness, poverty, and inequality (MIDSA 2009; New Growth Path Initiative 2009). Unplanned rural to urban population shifts place further strain on already overcrowded high-density locations close to and within major towns and cities. These locations are characterized by poor amenities, antisocial habits of crime and drug abuse in the setting of poverty, and unemployment and hopelessness, creating the perfect milieu and negative feedback loops that feed into the HIV epidemic (Bolton and Talman 2010). Lack of organized housing infrastructure in these localities will result in increasing exposure to indoor and outdoor air pollution, flooding and dampness, water and environmental pollution, and risk of fire, violence, and abuse (Holloway et al. 2010; Kilian et al. 2005).

In South Africa, the urbanization rate now is estimated to be 62% to small towns and cities, with rapidly growing informal settlements usually on degraded or unsuitable land (SADB 2008; South Africa's Second National Communication on Climate Change 2011). Crowded urban settlements are associated with an increase in social diseases, stress, and negative impact on vulnerability indices as previously described. (Pachauri and Reisinger 2007; Kilian et al. 2005).

Butler and Harley (2010) classify the threat of climatic and ecological effects to human well-being in three dimension in the form of the primary direct effect such as the acute impact of heat waves or flooding; secondary indirect effects produced by changing epidemiology of infectious disease; and tertiary effects, which are more serious and encompass famine, mass migration conflict, epidemics, and war and urge the medical profession to view this complex phenomenon holistically and in all its ramifications.

The relationships between HIV, the environment, and climate are interrelated and very complex with multiple pathways and negative feedback loops and have features that cross over from Butlers description of secondary and tertiary impacts of climate change. Impoverishment is the end point of all these factors and negatively affects the ability of individuals and collectively as communities to rise to challenges and cope with new stresses, hazards, and shocks. Methods by which affected individuals respond to stress may be beneficial as in positive adaptations or retrogression depending on social structures, access to information, or availability of resources. Ultimately, if wrong choices are made increased vulnerability of communities to HIV and environments to degradation can and will ensue (Butler and Harley 2010; Stillwaggon 2006). HIV is often perceived in its simplistic terms of engaging in risky behavior without understanding the context in which these choices are made. Poverty creates vulnerabilities that determine certain human behavior, sometimes beyond the thresholds of reasonable decision making. This increases vulnerability to HIV infection, which in turn creates further poverty in downward spiraling cycles of human and environmental degradation. Africa has been impoverished by decades of injustice, harsh weather patterns, PEM, and a complex myriad of infective agents in the setting of limited access to medical resources. If adaptations are now going to be effective, then the processes that produced the disenfranchisement should be addressed and the population reempowered to make adaptive and grass roots decisions in the context of self-determination and indigenous knowledge systems (Pettengell 2010; Stillwaggon 2006).

Under the auspices of the WHO Regional Committee for Africa, the framework for public health adaptation to climate was adopted by all regional health ministers by committing to identifying and documenting baseline parameters of risk in concert with capacity resources both human and infrastructure within the region and aligning this to the index of vulnerability with a view to ramping up health infrastructure as an adaptive measure. These would embrace overlapping goals within the MDGs and lay focus on water and sanitation.

In South Africa specifically, attention is directed at HIV, TB, and PEM through several strategic initiatives within the Department of Health (DOH). There is a critical shortage of health care personnel across the continent characterized by a brain drain not only from the public to the private sector but also from loss of human capital to developed economies. To achieve the goals outlined by the policies clearly laid out by regional ministers of health and particularly the DOH in South Africa, greater attention must be paid to producing more health care personnel and improving conditions of service that prevent this drainage phenomenon in this key sector. This can only be achieved by greater health care allied sector financing as a percentage of the GDP expenditure. A concerted and determined effort backed by strong political will and engagement is required to galvanize a robust and strategic approach to a multitude of deficiencies within our national and subregional institutions. Furthermore, the approach needs to be driven by an intersectorial framework with a common agenda aimed at strengthening multiple public infrastructures and resilience rather than the isolated attempts of each segment of public service attempting to rise to the challenge, which will inevitably be a weak and compartmentalized in approach and impact. The multiple foes affecting the community all have in common a unified denominator of success that resides in raising standards of living and both human and institutional resilience (New Growth Path Initiative 2009; AsgiSA 2012).

1.11.8.1 HIV/AIDS

Despite a national policy for initiating ARV treatment at a CD4 count of 200/μl (the CD4 blood count measures the damage to the immune system and is used to trigger various treatment strategies), most PLWH are starting ARV therapy at counts less than 100/μl (Avert 2010). Furthermore, the ARV program coverage rate is currently only 30% effective. This reflects the inadequate identification and recruitment of PLWH who qualify for treatment, which may be related to issues of stigma and lack of information. The consequence of this late commencement of ARV is poor regeneration of the immune systems, leading later to major morbidity and mortality and eroding the initial benefits of ARVs (Abayomi et al. 2011). There are clear immediate and long-term clinical benefits to starting ARVs at a minimum CD4 count of 200/μl (Badri et al. 2006; Kaufmann et al. 2005), and there needs to be greater efforts to achieve the goals set by the national policies. The initiation of ARVs at a threshold of 350/μl in pregnant women has been shown to virtually eliminate vertical transmission and is likely to be highly cost-effective (Mofenson 2009; Mofenson et al. 2009). Similarly, earlier initiation of ARV in PLWH who are coinfected with TB is likely to lead to significant savings (Lawn et al. 2007; Lawn and Wood 2007a,b).

For these reasons, South Africa has changed its policy as of 1 December 2009 to expand the ARV program to include pregnant women with CD4 counts ≤350/μl (Harrison 2010b). However, for the rest of the population, all efforts should be made to commence ARVs as close to a CD4 count of 200/μl as possible, although it appears that national policy is swinging toward adopting 350/μl as a standard threshold for commencement of ARVs for all. Initiatives focused on the manufacturing of ARVs in South Africa and finding more cost-effective indigenous platforms to carry out HIV testing and laboratory monitoring, as these currently account for 80% of costs of ARV programs, are in progress and highly laudable (Cleary et al. 2010; Cleary and McIntyre 2010; Kevany et al. 2009). The DOH of South Africa backed by powerful Government will has also initiated an ambitious program to identify all persons living with HIV through massive nationwide counseling and testing drives, which should provide a much-needed basis for aggressive recruitment into ARV treatment programs (DOH 2011).

Stigma barriers need to be overcome, and greater emphasis needs to be placed on encouraging the population to identify their HIV status and present early for sustained medical attention characterized by early commencement of ARVs with good adherence, which will translate to beneficial immune recovery (Sabin and Phillips 2009).

1.11.8.2 Tuberculosis

Ideally an effective vaccine against TB would have dramatic preventative impact especially in the context of drug-resistant strains. However, no progress has been forthcoming on this front, and the existing BCG vaccine only has temporary effect on children in their formative years, protecting them from severe complications of TB should they acquire the infection (Abu-Raddad et al. 2009). TB can usually be cured by a 6-month regimen of treatment. However, multidrug-resistant TB requires more sophisticated and costly treatment (Lawn and Churchyard 2009). The emergence of this phenomenon represents a major public health threat in South Africa, not just to the community but also to health care providers (DOH 10 point plan progress report 2011). Managing TB, especially multidrug-resistant TB, requires a heightened response with a focus on earlier detection at community level, improved patient compliance, and adequate drug sensitivity profiling (Basu et al. 2009).

Recent developments utilizing the new molecular-based test for DR-TB also known as the GeneXpert is about to be rolled out across South Africa as it provides fast and rapid identification of drug-resistant strains of TB on sputum smear-positive cases in a matter of hours as opposed to 6 weeks by conventional drug sensitivity mycobacteria growth indicator tube (MGIT) testing (DOH DR-TB report 2011). Health care environments must have suitable safety features to protect both caregivers and other patients. Particular attention must be placed on minimizing interruption and defaulter rates with good monitoring of smear-positive conversion rates after 2 months of TB treatment as a first benchmark of good response (DOH 2011). The ability to distinguish latent quiescent infection from active TB, particularly in HIV patients, is critical. Many HIV patients who have concurrent TB will be sputum negative and therefore not be amenable to standard laboratory diagnostic tests, which rely on the presence of the TB bacillus in the sputum. Ground-breaking work in identifying blood tests that can rapidly make these distinctions is being carried out by scientists from the continent (Adekambi et al. 2012; Chegou et al. 2009; Walzl et al. 2011; Djoba Siawaya et al. 2009). TB must be identified early in both its latent and masked active forms irrespective of sputum positivity, such that appropriate treatment can be commenced to protect the community and health care human personnel by pharmacologically quarantining the infective agent, thus minimizing its capacity to be transmitted to both normal and particularly vulnerable members of the community.

1.11.8.3 Nutrition and Health Infrastructure

At the heart of all health adaptation strategies must lie sound nutritional policies. If a population's nutritional status is robust with attention to the correct balance between proteins, energy, lipid, and micronutrients, then individuals will have greater resilience. More attention needs to be paid to children's nutritional status and particularly girls who will become key determinants of their future family nutritional profiles (Chapman et al. 2011). The interaction between malnutrition and infection requires focused attention to effectively combat prevailing and potentially emerging infectious epidemics (de Waal and Whiteside 2003; Macallan 2009; Keusch 2003). Health care capacity is a key component of developmental growth and stability and central to all adaptation strategies. Poor infrastructure and inadequate human resource is a barrier to any governmental plans for rural and urban welfare and alleviation of poverty goals. Issues of spatial location of health facilities, retention of skilled human resources, incentives to attract these resources to rural communities are all key issues that need urgent attention.

1.11.8.4 Drastic Circumstances Need Drastic Solutions

The turn of the twentieth century saw the advent of the antimicrobial, when man accidentally stumbled upon the biological agent known as penicillin. This happened in parallel with the industrial age ushering in the dawn of antimicrobial therapy with the advent of the hypodermic needle, establishing an era characterized by a surge in medical knowledge, use of antimicrobials, vaccinations, and organized health care delivery (Daily and Ehrlich 1995b; Marx et al. 2001). This created the environment for a dramatic increase in human population from about two billion in 1927 to a staggering seven billion in just under 100 years, and is estimated to grow to eight billion in the next 20 years (UN population figures).

The consequence of this dramatic population boom is inevitable food insecurity (McMichael 2001). This era has been characterized by massive rural to urban shifts and aging populations, which has worsened access to food and space for recreation. It is also attended by a rapidly growing human ecological footprint, increasing emission of fossil fuel into the atmosphere, environmental degradation, and the formation of giant agglomerations or megacities (Daily and Ehrlich 1995c). With exponentially increasing technical and medical expertise, humanity has stepped into the genetic age. We are currently living in the genetic manipulation era, which is characterized by man's capacity to successfully and rapidly sequence the entire genetic programs of all life forms. With this in mind there is the great temptation to explore the possibility to completely take responsibility for modifying the environment that we live in by creating biological organisms with modified genetic information that will meet the needs of a growing and high demand populace in a deteriorating ecological environment (McMichael and Woodruff 2002; Abayomi and Jacobs 2009). We may even be forced to modify the human genome to cope in a rapidly degrading and resource-constrained world that is losing the benefits supplied to human societies by natural resources. In the absence of a vaccine solution for the HIV scourge and the huge logistics of keeping millions of people alive in a region that is struggling to feed itself in hostile climatic conditions, the ARV roll out programs are expensive, technically cumbersome, and probably in the long run unsustainable. A drastic solution is needed now more than ever.

1.11.9 Conclusion

Despite Africa's incredible endowments in human diversity and natural resources, the impact of the HIV/AIDS epidemic has caused most economies of the countries south of the Sahara to experience reversal trends synonymous with economic backpedaling. This is why the simplest of goals known as the MDGs seem almost too high a dream to achieve. When one imagines that in fact the MDGs are not development goals by any stretch of the imagination but in fact simply targets to attempt to pull a whole continent out of share and abject poverty, it would only be at the point of attaining the MDGs and some semblance global social justice that Africa as a geopolitical space can speak of embarking on a new road of development. Coupled with shrinking global economies, the effect of HIV on human health, our most important resource, has been nothing short of catastrophic especially as the continent just seemed to be emerging out of the successive throes of slavery and colonialism in the mid-twentieth century. It appears that the continent has not been allowed to develop a stable and critical threshold of human capital to grow and drive its potential for sociotechnical development and geopolitical stability. Like a sleeping giant trying to emerge out of the rubble, the continent is now faced with further deterrents to growth in the form of threats from climatic conditions. However, perspective should be maintained and changes in climate statistics represent only a subset of climate, and even if there would be a change in these statistics, the other threats reviewed in this chapter show them to be dominant. Climate in all its ramifications is not a new phenomenon but is a series of events that has insidiously and perniciously crept up over the decades slowly corroding economic stability by further undermining the health and productivity of the continent. Most feared of all are its twin potential to undermine the livelihood and well-being of the people most dependent on stable or predictable climate and the latent ability to induce conflicts over water and arable land. The linkages between climate and HIV are numerous and intertwined at so many levels, and it is impossible to say where one starts, for until today one cannot say for sure which came first and when it started. Their negative impacts seem to feed off one another synergistically to the detriment of all people on the continent. What is sure is that we must overcome both menaces with the full might of the collective resources of humanity if we are to emerge victorious, and the world cannot sit back and watch Africa solve the problem on its own, because in the spirit of Ubuntu we are all one and live for one another. Extreme poverty, disease, and suffering in one part of the world creates instability and unrest in another. South Africa and its surrounding countries are contending with a major public health threat created by HIV and the attending downstream medical and livelihood complications that ensue in an environment with high prevalence rates. These effects culminate in the increasing vulnerability of the affected population and the ecological environments that are subject to exploitation when other options for livelihood are limited.

Multipronged strategic and measured approaches are required to alleviate now the double scourge of HIV and climate on the subcontinent of Africa, but central to the tasks are the alleviation of disenfranchisement and the restoration of self-governance and determination. The cost of mitigation and adaptation must be borne by the collective humanity as a separate entity to the huge needs to address underdevelopment through the MDGs. HIV and TB must be tackled face on as a global emergency and not as a business opportunity for the pharmaceutical industry and medical fraternities. Nor should it be turned into an exercise of rhetorical aid agencies branding imposing solutions on indigenous people. A radical simple and effective solution to pathogenicity of HIV needs to be found in the interest of humanity and should be devoid of commercial capitalization.

The solution to the eradication of the HIV/AIDS problem has been in our grasp for decades, yet there are millions at risk and millions dying on a yearly basis, dying at an age when they could be most constructive to the economic and political development of the nations of Africa and the world as a whole. For every person's premature demise and unfulfilled life is a loss to the world as a whole. Nelson Mandela, whose last surviving son died of AIDS, the icon of freedom and social justice, spoke these words in 2004: "By all accounts, we are dealing with the greatest health crisis in human history. By all measures, we have failed in our quest to contain and treat this scourge." Eight years down the line, we are no further toward achieving a solution, and with climatic change hot on our heels we are at critical times in our history.

Given what we know now about the evolution of pathogenic virulence, the nexus between human exploitation, environmental integrity, climate, social interactions, conflict, malnutrition, and disease, empirical evidence strongly supports a premise. Climatic and human–environmental conflicts may have not only been the catalyst for the evolution of HIV as a lethal human pathogen but also the precursor of the human social dynamics that have been so instrumental in the wide propagation across the continent and the globe. For the sake of posterity, social learning should trigger alarm bells when such circumstances coalesce as an early warning signal for new or reemerging diseases. As the famous historian Robin Weiss states, "the red, white and pale horses of the apocalypse representing conflict, famine and pestilence ride well together," it is often forgotten that preceding these three horses was the white horse representing the philosophy of exploitation (New Testament Bible; Book of Revelations, Chapter 6). All efforts now should be aimed at relieving the human exploitative pressure on land and other human beings and mitigate the negative effects of climate change. Improving livelihoods and the well-being of families with adequate nutrition would reduce the likelihood of HIV infection and its complications. While these mitigation and adaptive processes are being implemented, scientists and funding agencies must focus on a definitive cure for HIV/AIDS, which should be delivered and implemented speedily and without prejudice. Eminent historians of health, population, and environment propose that with the spread of communication and advances in science and technology it should not be too difficult to restore the earth to a state of natural harmony and reduce the exponentially rising impact of human populations on the carrying capacity of the earth through a more equitable existence. We should be cognizant of the fact that at the rate we are proceeding if we do not have a strategy by design we may end up with an undesirable culture by default.

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1.12 Occupational Health and Safety Impacts of Climate Conditions

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Glossary

CDC MMWR Centers for Disease Control (USA), Mortality and Morbidity Weekly Record

GHG Greenhouse gases

Heat exposure The actual thermal environmental (climatic) conditions quantified in a way that indicates the likelihood of heat stress. This variable can be calculated from climatic data (weather station data) or specially measured data. Heat exposure depends on air temperature, humidity, air movement, and any direct heat radiation (outdoors usually from the sun). Measure air temperature and humidity (can be done with cheap dataloggers). Add wind speed and heat radiation if possible, but these can be estimated.

Heat strain Heat strain is the effect on the individual from the heat stress. Heat stress eventually increases core body temperature when heat gain is greater than heat loss. A limited increase in core body temperature and subsequent sweating is part of the normal physiological reaction to heat stress and comprises low and reversible physiological strain. At higher levels of heat stress, the physiological strain on the human body is sufficiently high to create symptoms of excessive noncompensable heat strain eventually leading to hyperthermia, heat collapse, or heat exhaustion. In extreme cases, severe heat stroke and even death occurs. The individual variation in heat strain can be estimated by physiological models that use as input the specific parameters of an individual. Items of importance include age, sex, pregnancy level of dehydration, physical fitness, and degree of obesity.

Heat stress Heat stress is a measure of the environmental influences that alter the heat gained and heat lost by the individual. The heat burden on the individual physiology, which is determined by the level and duration of 'heat exposure,' the persons' physical activity intensity (metabolic rate), and the persons' clothing. Heat stress can be reduced by avoiding direct sunshine, using suitable clothing, or reducing metabolic rate, which for working people means working less intensively and taking more rest breaks. An increase in sweating (except at high humidity) and a limited work regime to prevent an increase of core body temperature are part of the normal physiological reaction to heat stress. Another aspect of heat stress is the extent to which the person is acclimatized to heat. This has a limit, however, and 'behavioral acclimatization' is an important aspect of the

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actual heat stress on a person. Quantification of heat stress should be based on physiological responses leading to 'rational heat indices.' It should be noted that there are individual variations in the association between heat exposure and heat stress, and statistical averaging is required based on the estimated risk distributions in populations.

IPCC Intergovernmental Panel on Climate Change

ISO International Organization for Standardization

NOAA National Oceanographic and Atmospheric Administration (USA)

UTCI Universal Thermal Climate Index is an indicator of perceived heat stress that takes into account climate variables, clothing, and limited physical activity (set fixed at walking 4 km h^{-1}). Calculation formulas based on weather station data are available on the website utci.org.

WBGT Wet Bulb Globe Temperature is an indicator of heat exposure that incorporates workplace air temperature, air humidity, wind speed (air movement), and both short- and long-wavelength heat radiation on the worker. Special equipment with three thermometers is available (check in Google).

1.12.1 Introduction

People working in hot environments are vulnerable to health effects of heat. The health effects include heat exhaustion, heat stroke (which can be fatal), and increased accidental injury risks in workplaces (Parsons 2003). Populations in large cities experience additional heat exposures because of the 'urban heat island effect' making densely built urban areas several degrees warmer than the surrounding countryside. Increasing air temperatures and/or humidity as part of local climate change would further increase these occupational health risks (Kjellstrom et al., 2009a, b, c).

Daily heat exposure during the hot season in tropical and subtropical parts of the world is a problem particularly for people working in jobs that cannot be, or are not, cooled by air conditioning or other technical methods. Intense physical labor creates substantial surplus heat inside the body, which must be released to avoid health-threatening increased core body temperature. When air temperature exceeds 37 °C, evaporation of sweat becomes the only mechanism to cool the body, but sweat evaporation is strongly impaired by high air humidity. Tropical climates with high humidity are therefore a particular occupational health and safety problem. The current hazards of excessive heat exposure at work in low- and middle-income countries have been referred to in a number of recent publications, and these are summarized in this chapter.

Protective measures include shading, fans, and cooling systems, but these do not protect at high humidity and may not be sufficient or possible to apply in certain jobs. In those situations, the most effective protective method is a reduction of internal heat production by, for example, taking more and longer rest periods during work hours with excessive heat exposure. However, these rest periods reduce hourly productivity and the daily economic output of the workers. Thus, this effect on occupational health and safety is also likely to undermine local economic development.

This chapter presents different methods to measure heat exposure and effects. Regional and global assessments of the impacts of climate conditions on occupational heat exposures and effects in different parts of the world will be presented. There will be practical advice on preventative measures to minimize heat stress and strain as means to adapt to climate conditions, including climate change as modeled by the Intergovernmental Panel on Climate Change (IPCC). Mitigation of climate change (reducing its extent) is not dealt with in detail, but it is, of course, another important means to prevent negative impacts on occupational health and productivity in countries at all income levels, if, as projected, the local heat exposure would increase in many parts of the world.

1.12.2 Current Climate and Ongoing Climate Trends

Many parts of the world, particularly tropical areas, already have climate conditions that are so hot that daily life, particularly for working people, is affected. Heat stress maps for the whole world have been produced by Jendritzky and Tinz (2009), and they show the high heat exposures present now and the trends toward higher exposures in the future.

The authors have used freely available daily weather station data from NOAA in the United States (their website contains daily data from many thousand stations around the world: the Global Summary of the Day, GSOD) to calculate and visualize the annual averages of daily maximum, mean, and minimum temperatures, dew point (an indicator of absolute humidity), wind speed, and rainfall for a number of locations in some of their publications. The graphs in Figure 1 show an example for a city, indicating typical trends of temperatures in cities of tropical and subtropical Asia. It is likely that these trends include significant impact of the 'urban heat island effect' due to urbanization, pointed out by Oke (1973). The figure shows the equations for fitted lines to the recorded data, and it shows that each of the temperature levels have increased by approximately 0.5 °C per decade during this 30-year period.

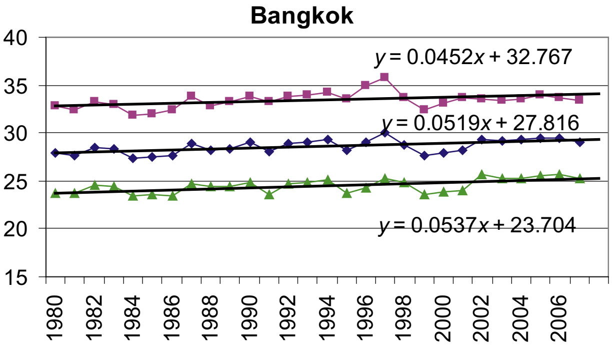


Figure 1 Time trends of annual averages of maximum (pink), mean (blue), and minimum (green) temperatures at Bangkok airport, Thailand.

In this chapter, the term 'climate change' is used as a way to refer to these ongoing changes of air temperature and humidity, as well as the future changes projected via careful modeling by the IPCC. Some people insist on using the term 'climate variability' instead of 'climate change,' but this obscures the notion that climate effects include those caused by human activities that emit greenhouse gases (GHGs) and aerosols, as well as from land-use change (NRC 2005).

In populated areas with extremely cold periods each year in the Northern Hemisphere (including the northern parts of Europe, Alaska, Canada, and Russia), the ongoing trend toward higher average temperatures can also be demonstrated; this will reduce winter cold stress in some occupations but may also increase heat stress in summer. However, clothing and other protective means against cold already reduce cold stress on working people. Cold conditions also induce people to work harder to generate more body heat. It is more difficult to protect workers against extreme heat without expensive and energy-intensive equipment such as air conditioners.

It should also be emphasized that the areas of the world with extreme cold climate are much less populated than the areas with extreme heat. In the Arctic, the population is less than 1 million, while in the tropical areas, the population is approximately 4000 million.

1.12.3 Different Occupational Health Effects of Climate Variables

Climate conditions, and particularly trends toward hotter environments, do affect various aspects of occupational health and safety as highlighted by Bennet and McMichael (2010). A few are listed here.

1.12.3.1 Extreme Weather Events

As concluded in the 2007 IPCC report, more energy absorbed and maintained in the atmosphere should increase the likelihood of extreme weather events: for example, hurricanes, tornadoes, typhoons, storms and rainstorms leading to flooding, and lack of rain leading to drought (see Chapter 2.1 of this book). Such conditions lead to injuries and other health risks for emergency workers, and the local affected populations may be injured and lose essential services, which increases health risks and has negative economic effects.

1.12.3.2 Occupational Heat Stress

This is the most direct effect of climate conditions, and this health hazard has been analyzed in detail by Parsons (2003). High air temperatures, especially in combination with high humidity, create physiological challenges and risks of heat exhaustion, heat stroke, and even death. The most extreme impacts of heat-related deaths during work are occurring even in developed countries like the United States as reported by the Centers for Disease Control (CDC) and the mortality and morbidity weekly record (MMWR 2008). This hazard is described in more detail below, and the reference list contains the main evidence relating to climate trends. There are also heat morbidity and mortality risks in the general population. At the other end of the climate spectrum, cold stress is a serious health hazard, which in areas with extremely cold winters may become less common if the local climate gets warmer.

1.12.3.3 Kidney Disease due to Daily Dehydration

Workers who are exposed to high heat levels while carrying out heavy labor lose large amounts of liquid via sweating each day: $1\ \mathrm{l\ h^{-1}}$ or even more can be sweated in such conditions. During a work-shift, the lost liquid may be 10 l or more, and if this liquid is not replaced by drinking water the worker develops dehydration. If as little as 2–3 l of lost liquid per day is not replenished the dehydration may lead to clinical symptoms of fatigue and related losses of work capacity. If dehydration occurs every day during long work periods, it is possible that clinical damage to the kidneys can occur. This could be one explanation for an epidemic of chronic kidney diseases currently occurring among sugar cane cutters in El Salvador and Nicaragua.

1.12.3.4 Increased Chemical Exposures

Many workplaces are using chemicals that evaporate at room temperature and create inhalation exposures in the workers. Of particular concern are the widely used organic solvents, as increased temperature of liquid chemicals increases the speed of evaporation of the chemical, leading to higher concentrations in the air at the place where the chemical is used. The absorption of these chemicals, especially the hydrophilic ones, is very high during high-heat situations and metabolic workload. The impact of these chemicals on workers working in different temperatures varies and hence the safety limits. Often the threshold limit values (TLVs) for such chemicals cannot be achieved universally for all occupational settings. This occupational health aspect of climate conditions has received almost no attention in research or analysis so far.

1.12.3.5 Vector-Borne Diseases

Some vector-borne diseases, spread by mosquitoes, are likely to be a particular problem for agricultural workers in hot locations. These diseases include malaria and dengue fever, and the climate connections are presented in a number of review publications, e.g., by Costello et al. (2009) and McMichael et al. (2003, 2004). If the daytime periods get so hot that only limited work can be carried out, the agricultural workers may spend more time working in the early mornings and late afternoons when the mosquitoes are the most active in biting humans. Thus, the risk of getting these diseases is likely to increase as the climate gets hotter, and the need for preventive measures increases.

1.12.3.6 Ecological Change Diseases

Climate change, in the form of increased temperatures of air, surface water, and soil and/or greater or lesser rainfall and air humidity, can be associated with ecological change that can create new health risks for working people. If the ecology changes locally, disease vectors or infectious agents (bacteria, viruses, and parasites) may spread to new areas and at different seasons than what is common currently. This will expose working populations to risks that they have been spared in the past. One example is the schistosomiasis parasite that spreads via snails in waterways (rivers, dams, canals, and rice fields). In China, these snails cannot survive in large areas of the country because the coldest periods are too cold. As the climate gets hotter and water temperatures in many waterways increase, the snails spread to new areas, and the risk for infection among local farming and fishing populations increase. It has been estimated that the expansion of the geographic area where this disease occurs in China as climate is changing will put many million people at risk. Occupational groups working in forestry and agriculture are exposed to new types of hazards that are not well understood, e.g., new species or new strains of vectors that the existing health system is unprepared to tackle.

1.12.3.7 Infectious Diseases

Diarrheal diseases are more common in areas with periods of high temperatures, as bacteria in foodstuffs can multiply faster when temperatures go up. In addition, higher temperatures in surface waters create greater risk of bacteria and virus contamination of drinking water. This is a problem for whole communities, and children are in general the most affected. However, working people may be at particular risk as they bring foodstuffs to work for consumption during lunch, and spaces for keeping the foodstuffs cool are not available. Of course, these health risks, just like the others mentioned earlier, are more likely to affect poor people without the ability to use protective methods. These problems have been described in Chapters 3.2 and 3.3 in this book.

1.12.3.8 Nutritional Security

Agriculture is naturally dependent on the local climate conditions. As climate is changing, leading to hotter temperatures in tropical areas and/or major changes in rainwater access, some places will have great problems maintaining local agricultural productivity that the local poor populations depend on. Extensive drought is already a problem in parts of Africa and Asia, and this leads to reduced access to food in the local populations. The main serious health problems are usually recorded among preschool children, but it is likely that working adults also get affected by lack of sufficient nutrition. This type of effect would not normally be included in the analysis of occupational health problems, but it is one feature of climate change that may become of great importance in some parts of the world. The increasing temperatures in very cold areas of the world are likely to increase agricultural productivity in those places (e.g., Canada and Russia), but this impact does not help poor working people in tropical areas.

1.12.3.9 Social Tensions: Mental Health

Another feature of climate and health that is of great importance in some communities is the social and mental stress associated with, for instance, local agricultural productivity. In Australia, it has already been reported that the incidence of suicides among farmers affected by long-term drought has increased. Similar stories emerge from India. The undermining of the livability in certain parts of the world because of local climate change has already led to 'climate refugees' abandoning places they used to live in and moving to other places. The mental and social stress for the refugees themselves and the communities of places they move to is becoming an increasing concern for international development agencies. Again, this is an effect on working peoples' health and livelihood that is seldom considered as a part of occupational health. The impacts of occupational heat stress also spill over to the families of the workers, as increased incidence of violence and unrest have been reported in studies of this concern.

It should be pointed out that working people are also affected by heat exposures outside of work. If hot temperatures impair the quality and/or quantity of the nightly sleep, this will decrease work capacity on the following day. In some jobs, commuting to and from work involves very high heat exposures. In addition, if heat prevention involves long breaks (siestas) in the middle of the hot days, and work very early in the morning as well as into the evening, the effect on family social connections may be very disruptive. High temperature and humidity also create mold problems in dwellings, with risks for allergies and fungal diseases. Thus, it is not just increasing heat exposures at work that can become a problem for working people if the climate is changing. Of course, air conditioning in residences and workplaces are becoming more and more common, but the energy cost is prohibitive for many people, and regular electricity cuts ('brown outs') reduce the cooling outcomes in many places.

As mentioned earlier, poor people in localities with extreme climates and climate that is heating up are the most likely to be affected by these work-related health and well-being hazards. Among working people, one can also identify a number of vulnerable groups:

- People working in heavy labor in tropical and subtropical countries during the hot season, particularly if their work has to be done in hot sunlight
- Workers who need to work continuously at high physical intensity
- Workers who need to wear heavy or impermeable protective garments
- Agricultural workers
- Construction workers
- Emergency workers
- People in vulnerable positions, for instance migrant workers
- Workers in factories or workshops without efficient cooling systems; a common situation in low- to middle-income countries
- Workers in slum workshops

1.12.4 Excessive Heat Exposure as a Special Occupational Health Hazard

The mechanisms of heat gain and loss by the human body are well understood and have been reviewed by Parsons and others. The main mechanism of heat gain is the heat generated by muscles that work at approximately 20% efficiency. Heat can be transferred to/from the body by convection, conduction, radiation, and evaporation of water (sweat). Air is a very poor conductor of heat, so the significant heat transfer mechanisms (unless submerged in water) are convection, radiation, and evaporation. Environmental factors that influence these heat transfer mechanisms are air temperature, wind speed, humidity, and radiation sources.

Heat gain = Heat loss + increase in stored heat. The increase in stored heat is reflected by a rise in core body temperature. While some increase in core temperature above 38 °C is acceptable, conditions where heat gain is greater than heat loss for prolonged periods lead to an increase in core temperature that is incompatible with healthy life. There is debate concerning the actual value of this critical core temperature (in the range 38–39 °C), and it varies from person to person, with ethnic groups, with age, with gender, and with the number of days at high heat exposure.

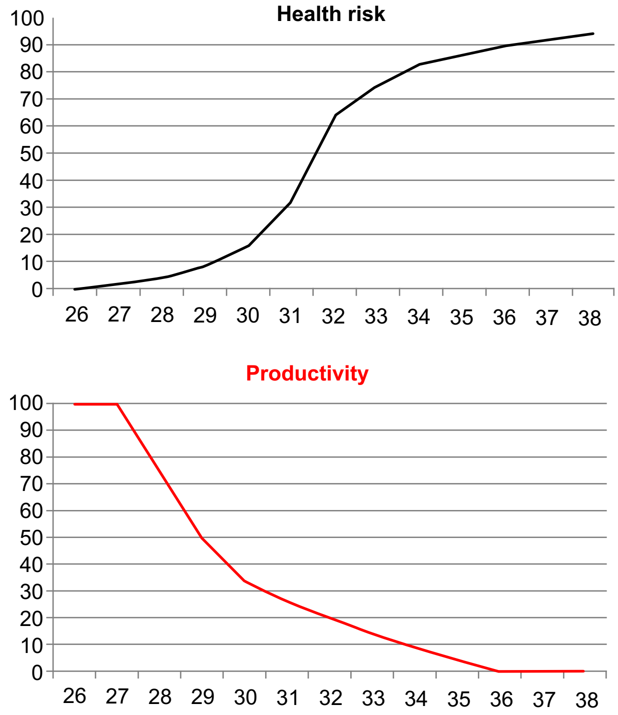
The ability of an individual to lose heat also depends on the degree of acclimatization, the number and activity of sweat glands, the cardiac output, the amount of blood able to be redirected to the skin for cooling, the degree of hydration, the surface area of the skin, and the clothes they are wearing.

If one is measuring the heat strain of an individual, all these factors must be taken into consideration. However, when giving advice to groups of people on the risk of heat stress, or researching the effects of climate conditions on heat stress, it is more useful to have a heat stress index that depends only on environmental variables. The wet bulb globe temperature (WBGT) is the most widely used index of this type and is used in national and international standards for recommended maximum workplace heat exposure (e.g., International Organization for Standardization (ISO) standards). Such recommended levels vary between countries and may be lower in cool countries (e.g., England) with occasional hot spells than in hot countries (e.g., India) where the population is more acclimatized and better adapted to higher temperatures. Using heat stress indicators helps the regulators or concerned authorities to predict the conditions based on weather forecasts and to be prepared for protection of the workers.

1.12.5 Occupational Health and Productivity Effects of Heat Exposures

The links between human physiology, climate conditions, and effects on health and work capacity have been discussed in detail in physiology and ergonomics texts, e.g., by Parsons (2003) and Bridger (2003). High heat exposure creates a risk of heat exhaustion and heat stroke and is subjectively perceived as unpleasant or dangerous. People working or involved in heavy physical activity are particularly affected as highlighted in the authors' publications (see References and Proposed Additional Reading), because physical activity produces additional heat in the body. A natural reaction of a working person to heat is to reduce physical activity, which reduces the body's internal heat production. An outcome of this preventive reaction is reduced hourly work capacity and reduced economic productivity during exposure to heat. Thus, the balance between health risk that increases with heat exposure level and maintaining productivity is an issue that creates occupational health problems of a difficult kind (Figure 2).

An enterprise can compensate for this heat effect by carrying out heat-sensitive work during the cooler night hours of the hot season or by scheduling such work into the cooler season, but if heating climate trends progress, the duration of 'cool periods' will diminish in many parts of the world. In addition, some work has to be carried out during daylight, which reduces the available



If WBGT goes up and the worker does not reduce physical labor output, productivity goes down somewhat, while heavy physical labor continues, and the risk of serious health risk (e.g., heat stroke) goes up.

If WBGT goes up and the worker reduces physical labor in accordance with occupational health standards, the productivity will go down substantially but the health risk will stay relatively low. Thus, the workers' action to preventive ill health results in lower productivity

Figure 2 The 'competition' between increasing health risk and increasing productivity loss due to workplace heat. Source: Kjellstrom, T., B. Lemke, and O. Hyatt, 2011: Increased workplace heat exposure due to climate change: a potential threat to occupational health, worker productivity and local economic development in Asia and the Pacific region. *Asian-Pacific Newslett. Occup. Health Safety*, **18,** 6–11.

'cool hours.' For instance, many agricultural workers need to work outdoors in the sun, and if their pay is based on their product output, they may work beyond safe heat exposure limits and die of heat stroke, even in the United States, as reported by CDC, MMWR (2008). If a worker chooses to work, the number of hours the worker can work safely without any physiological impact reduces, thereby reducing income and the economic performance of the community. The mechanisms behind the health and productivity effects of heat, and the relationships to climate change, have been described in some detail in recent reports available for free on the web (see Global Health Action 2009, 2010) and will not be repeated here.

1.12.6 Measuring Heat Stress and Strain

Measuring the effects of heat stress on humans has many perspectives. For health and safety issues: the effect of heat stress on an individual undertaking a particular activity. For forecasting purposes: the effect of heat stress on the people in a particular location (such as a city). For long-term impacts of a hotter climate: the effect of heat stress on the population of the world.

Measurement of heat-related health risks fall into two categories: heat stress and heat strain as highlighted in the Glossary. Conventional engineering terminology defines stress as external forces and strain as the response by the object or individual to those stresses. As such, heat stress is a measure of the environmental influences that alter the heat gained and heat lost by the individual. Heat strain is the effect on the individual from the heat stress. This is very dependent on the individual, where they live, what they do, and what they wear. It can be altered by working less hard, moving to a cooler location, changing clothing, shading, fanning, and cooling down in water.

If the quantity of individual heat strain is required to be known, physiological models exist in ISO standards to calculate heat strain. These include the required sweat rate model, the Physiological Heat Strain (PHS) model by Malchaire (2006), the US Air Force model, and the Fiala et al. (2001) model.

While there are numerous indexes to quantify heat stress (as highlighted by Parsons (2003)), the authors focus on WBGT because this is the best developed index for workplace applications with rest/work cycles clearly specified under different work conditions. The heat stress standards at both national and international levels indicate that for people working in heavy labor a WBGT level above 26 °C requires hourly rest periods away from the heat to avoid core body temperatures rising to a dangerous level. For lighter labor, like inside a factory, the threshold for rest periods is at 29 °C.

If one documents an increasing trend of calculated WBGT (indoors in the afternoon) in a location, it is a sign of climate variability and can also be a sign of ongoing climate change on top of the variability. The authors used routine local weather station data with new software, designed by their team, to display the climate trends. Figure 3 shows the situation for a major city in the eastern part of Thailand: the number of days each year when calculated indoor WBGT in the afternoon is above 29 °C. This is the upper 'tail end' of the local heat situation, but it gives a vivid picture of the number of days when work productivity can be affected by increased rest periods, or when heat stroke health risks are increased if the workers do not take breaks. There is a great variability from year to year, depending on underlying weather variations (possibly due to the El Nino–Southern Oscillation (ENSO) annual impacts). However, if a line is fitted to the data, (Figure 3), the general trend is an increase of extreme heat stress days from approximately 60 per year in 1980 to approximately 110 per year in 2011. Thus, the annual period of extremely hot days for working people has lengthened by a month during these 32 years.

1.12.7 Occupational Health Standards and Guidelines

The WBGT index includes the impacts on three thermometers from four environmental climate factors (temperature, humidity, air movement, and solar radiation) and so does not depend on individual differences. The ISO standard used in conjunction with WBGT then relates the WBGT level allowable for different clothes, different levels of work, and other individual characteristics.

The heat strain is addressed by the ISO (1989) and national standards that outline the conditions to minimize the effects

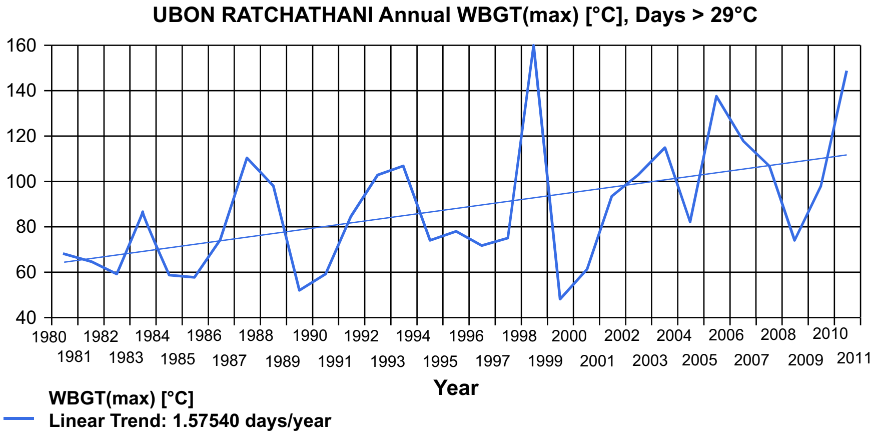


Figure 3 Number of days each year when calculated WBGT indoors in the afternoons (the hottest part of the day) exceeds 29 °C in the city of Ubon-Ratchathani, Thailand.

on the individual. The ISO uses WBGT to recommend maximum hourly limits for work in hot environments in order to ensure that average core body temperature of workers is not higher than 38 °C. Many countries have national standards for heat strain at work that gives organizations a guide to what precautions to take when the heat stress reaches a certain point.

The ISO standard identifies maximum WBGT levels for continuous work (hourly), 25% rest during a work hour, 50% rest, and 75% rest, which can be used to analyze the reduction of hourly physical work capacity as WBGT increases. These standards are based not on average responses to heat stress but on the response of the most vulnerable 5–10% of the population, as it is undesirable to have anyone suffering from the effects of heat strain. Part of the action plan once the heat stress gets above a certain point (TLV) is to make more detailed heat strain measurements on individuals to ascertain whether an individual is suffering from heat stress or not.

The WBGT index was developed after detailed studies by US military ergonomists in the 1950s. While WBGT has been criticized by Budd (2008) and others, it has all the correct components to indicate physiological heat stress. One criticism of WBGT is that it is too stringent for determining conditions when full workload should be reduced. This criticism has less to do with the WBGT index than the ISO standard criteria for reduction of workload. For instance, Nag et al. (2009a,b) considered that an increase in core body temperature up to 39 °C was acceptable or tolerable, while ISO limits the increase to 38 °C. The risk of heat stroke increases with an increasing core body temperature, so the 'margin of safety' will be less if 39 °C is used as compared to 38 °C. It all depends on how much discomfort and health risk is regarded as 'acceptable.' The ISO standard is currently being updated in order to address some of these criticisms.

New heat stress indexes such as the Universal Thermal Climate Index (UTCI) are based on the heat balance mechanisms of the human body. They are difficult to use at the workplace because conditions vary all the time: People change their clothes, clouds pass over, different movement creates different apparent wind speed, and walking and bending over expose different body profiles to the sun. This continuously changes the mean radiant temperature and air movement experienced by the worker – two key components for the UTCI calculation. Further, little research has been published for this new 'rational' heat index in relation to work/rest cycles to prevent excessive increases in core temperature in the majority of workers at a workplace.

Mathematical formulas to calculate WBGT and UTCI based on weather station data have been published. The authors recommend the Liljegren or Gaspar methods for outdoor WBGT and the Bernard method for indoor WBGT (Liljegren et al. 2008; Gaspar and Quintela 2009; Bernard and Pourmoghani 1999). Unfortunately, some formulas available over the Web are incorrect and should be avoided. In calculations of indoor WBGT the authors assume a wind speed of 1 m s^{-1}, as this would represent the speed at which arms and/or legs would be moving through the air for a worker carrying out physical labor. For indoor calculations, one can assume that solar heat radiation is not present.

1.12.8 Reported Experiences of Workplace Heat Exposures and Effects

A number of recent publications in the journal *Global Health Action* have described the heat stress experiences of working people in several countries. It is clear that in many jobs people are used to take preventive actions, such as refraining from working during the hot afternoons (aka siesta) or replacing heavy labor jobs in hot environments with robots or other technological solutions.

It is surprising, however, that quantitative estimates of the exposure–response relationships between heat exposure and health risks or work productivity losses have received little research attention during the last 50 years. In the 1950s and early 1960s, Dr Wyndham in South Africa published a large number of reports on the heat effects on gold mine workers. Table 1 shows how the heat effect risks increase as the estimated level of heat exposure increases. The research was aimed at finding ways to reduce the serious clinical health effects of heat (including deaths) at mine depths of 1 km. One reason for fatalities was the time it took to take a worker out from the mine if he developed heat stroke symptoms. Dr Wyndham developed and tested an 'acclimatization chamber' at ground level, and new workers were exposed to heat similar to that found underground while doing strenuous exercise at similar metabolic rates as needed for the work underground. The exposure in these chambers continued for 2 weeks, and the percentage of new recruits who could cope with the heavy labor at the high heat exposures increased from 14 to 29%. This indicated the acclimatization that was achieved in some workers, but it should be stressed that even after the chamber exposure for 2 weeks, 71% of the new recruits could not cope with the heaviest underground working conditions. Dr Wyndham's studies also included analysis of productivity

Table 1 Heat effects on gold mine workers in South Africa in the 1950s and 1960s

WBT, °C	*Approximate number of workers*	*Nonfatal heat stroke rates per million workers per year*	*Fatal heat stroke rates per million workers per year*	*Loss of work productivity, percentage of hourly output*
< 27	371 318	1.6	0	0
27	177 960	6.7	0	2
30	178 536	49	17	15
32	89 113	139	36	32
33.5	15 507	320	114	45
35	1800	889	666	60

Wet bulb temperature (WBT) levels of heat exposure are similar to WBGT levels; data from a 6-year period (Based on data in Wyndham, C. H., 1969: Adaptation to heat and cold. *Env. Res.*, 2, 442–469.).

Table 2 Summary of heat-related health effects and productivity losses in industries in southern India

Type of industry	*Employees with health effects (%)*	*Employees reporting productivity loss (%)*	*Managers reporting productivity loss (%)*	*Safety expenditure due to heat stress (%)*
Auto manufacturing	44	29	17	54
Chemical manufacturing	65	60	8	4
Hotel industry	86	44	73	14
Construction industry	92	90	68	50
Support services in healthcare industry	67	38	40	20

Venugopal, personal communication.

losses at different heat exposure levels (Table 1). It is not clearly stated in the reports, but one can assume that only the workers who passed the ‘acclimatization test’ were sent underground for daily work. These are the most quantitative estimates of heat health risks in real workplaces that have been published. It must be borne in mind that in spite of acclimatization and adaptation to changing climatic conditions, the human body can perform only within certain limits, beyond which it is accompanied by physiological decrements and productivity losses. There is a great need for further quantitative studies of heat effects.

A more recent example is the data collected in factories in South India during studies in 2011 (Table 2). The studies cover heat measurements and interviews with workers and supervisors representing hundreds of workers in the types of factories listed. The prevalence of heat-related health effects is very high in some industries, and productivity loss is a common issue reported by both workers and managers. Additional workforce is employed to achieve the company’s productivity targets, which impacts the industry’s budget directly. Indirect expenses include training costs, especially in outdoor occupational sectors, where there is a high turnover of the workers during summer months when the workers are not able to cope with the workload and the high ambient temperatures. It is also interesting to note that in some industries a large proportion of the safety expenditure is related to reducing heat exposures and effects during summer months.

Additional examples from India have been provided by Ayyappan et al. (2009), Balakrishnan et al. (2010), and others, and examples from Thailand, Taiwan, South Africa, Cameroon, Nicaragua, Costa Rica, and other countries are given in *Global Health Action*.

1.12.9 Estimated Impacts on Occupational Health of a Subset of Projected Future Climate Change with Increasing Heat Exposures

As mentioned earlier, many places in tropical or subtropical countries already have daily maximum heat exposures higher than levels interfering with work productivity and health protection at work. Projections into the future further emphasize the heat impact risks that could develop. Figure 4 shows as an example of one of the hottest months in Asia and the IPCC model projections from 1975 to 2050 of increased indoor WBGT levels in the afternoons. Parts of Pakistan and Northern India are projected, based on the IPCC modeling, to be so hot that any kind of physical work will become physiologically impossible. It should be pointed out that mental work is also affected by high heat exposures as described in studies by Hancock et al. (2007).

Large parts of Asia, including densely populated areas in India, China, and Southeast Asia, will have afternoon indoor WBGT levels above 30 °C, which will significantly reduce hourly work capacity. The exposures presented in Figure 4 are monthly averages; so individual days will be even hotter. In addition, it should be pointed out that outdoor heat exposures in the afternoon sun may have approximately 3 °C higher WBGT values, which indicates major heat stress for workers in agriculture, construction, and so on.

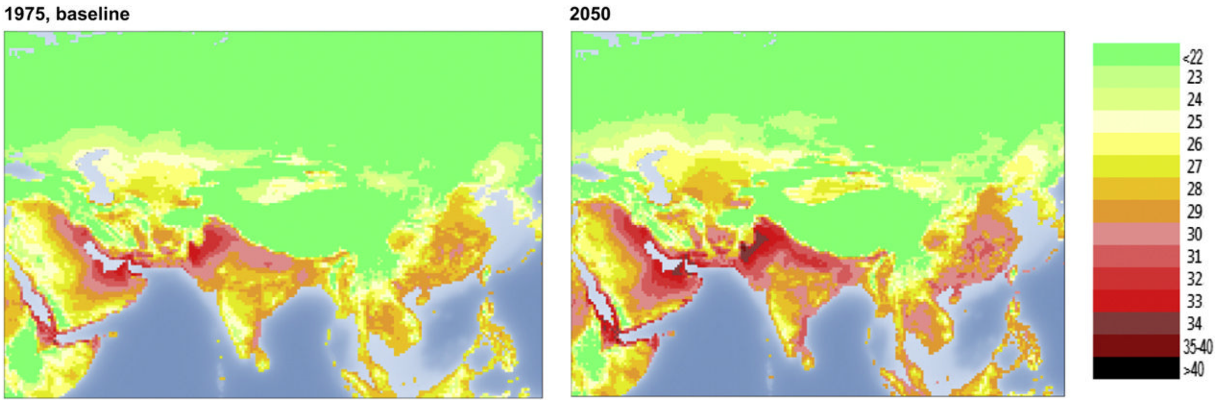


Figure 4 Global grid cell (0.5 × 0.5°) based maps of averages of daily maximum WBGT levels indoors during July in Asia in 1975 and predicted for 2050 (based on the BCM climate model). The color scale indicates the WBGT levels.

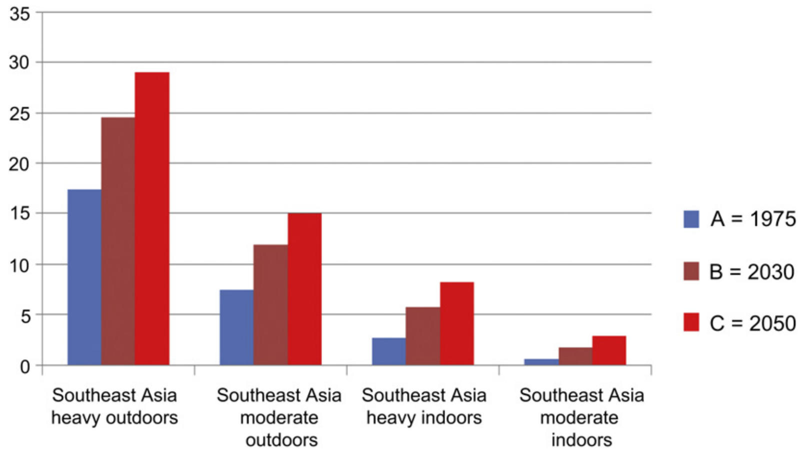


Figure 5 Percentage of annual work capacity loss in moderate–heavy physical work due to workplace heat exposure, Southeast Asia, based on climate model outputs for 2030 and 2050 (based on the BCM climate model).

The authors' research team is working on detailed assessments of workplace heat exposures using this type of modeling outputs and is estimating the impacts on different occupations. If each daylight working hour in a year is assigned with a specific WBGT exposure level, one can calculate the impact depending on the degree of physical activity in different jobs and whether they are carried out indoors or outdoors. Figure 5 shows the result for Southeast Asia. In heavy outdoor work, the loss of work capacity (expressed as percentage of all daylight work hours lost per year) in the 1975 climate was 17%, which then increases to 24 and 29% in 2030 and 2050, respectively. The losses in moderate outdoor work or heavy and moderate indoor work are less, but the trends with the projected increase of excessive heat days go in the same direction. The next step would be to estimate the related economic losses, but this has yet to be done.

When these methods are applied to a region using the grid cell heat exposure change and working age population within each grid cell, one can calculate the occupational heat stress impacts at a regional level. An example for East Asia (mainly China), with an estimated working age population at 768 million in 2050, is shown in Table 3. These calculations were made with three different climate change models recommended by WHO [BCM (Bergen Climate Model, from Bergen University, Norway), EGMAM (ECHO-G^2 with Middle Atmosphere and Messy interface climate model, from Free University Berlin, Germany), and IPCM (Institute Pierre Simone Laplace -Climate Model, from Institute PSL, France)], and the table shows baseline values for 1975 (actually the average of 1961–90) as well as the 2050 exposure and impact results.

Table 3 indicates which impacts can be expected if the climate becomes hotter. The exposure change is indicated by the percentage of grid cell person months when WBGTmax (in the afternoons) is greater than 26 °C. Then come clinical effect risks per million working people and the percentage work capacity loss per working person (based on loss of daylight work hours). By applying the size of the working population in 2050, one can also calculate the estimated number of sick cases and work hours lost. The details will not be repeated in the text here, but it is clear that a high percentage of loss in work capacity and millions of work hours lost in the population will have economic and social consequences for families, communities, and whole nations. Preliminary findings of our studies in India show that workers spend about 2–8% of their income on heat-related issues, including medical expenses, adapting to changing climate, and protecting themselves from the impacts of heat stress.

1.12.10 Methods to Reduce Heat Exposures and Effects

There are good descriptions of heat prevention approaches in reports by Parsons. The special challenge is of course that the prevention of health risks in many work situations creates loss of work capacity and work productivity.

Mitigation of climate change is therefore an important way to reduce the increase in heat exposures in workplaces and the related occupational health risks. However, good natural ventilation inside workplaces and, when necessary, air conditioning can make a big positive difference. The focus should also be on strengthening and improving the local occupational health management programs in collaboration with the workers themselves. This would be in line with international recommendations and standards. Free access to clean drinking water is a major requirement in jobs that are associated with heavy sweating. This would prevent dehydration, which is a serious health and performance risk.

When planning and building new workplaces, whether factories or other work situations, it is important to consider the design to reduce future excessive heat exposures. Keeping trees or other creators of shade around a workplace is important, as well as architectural methods that reduce overheating of the roof or walls. Black roofs are particularly bad as they absorb and transfer solar heat indoors, and an effective heat-reduction design can include two roof layers with air or other insulation in between. Natural cooling systems inside buildings can also be designed to reduce local heat stress. Any heat emitting part of the factory engineering facilities should be located in a place isolated from the workers.

Table 3 Listing of all predicted occupational heat stress impacts in 2050 in East Asian region (based on the BCM climate model)

Variable	*Baseline (1975) (A)*	*BCM*	*EGMAM*	*IPCM*	*Average of the three models (B)*	*Difference B−A*	*Ratio B/A*
Fraction of all grid cell person-months of heat exposure when WBGTmax >26° C (%)							
	12.3	18.3	19.2	21.4	19.6	7.3	1.6
Clinical effect risks, heat strokes, per million working people							
Fatal heat strokes, outdoor	3.4	6.3	7.8	10.1	8.1	4.7	2.4
Fatal heat strokes, indoor	0.03	0.8	1.6	2.2	1.53	1.50	50
Nonfatal strokes, outdoor	12.0	22.3	27.4	33.6	27.8	15.8	2.3
Nonfatal strokes, indoor	1.1	3.9	6.0	8.0	6.0	4.9	5.5
Work capacity loss of daylight work hours per working person (%)							
Heavy labor, outdoor	3.65	6.26	7.21	8.45	7.31	3.66	2.0
Heavy labor, indoor	0.59	1.54	2.10	2.69	2.11	1.52	3.6
Moderate labor, outdoor	1.6	3.0	3.7	4.5	3.77	2.17	2.4
Moderate labor, indoor	0.2	0.5	0.8	1.0	0.78	0.58	3.9
Light labor, outdoor	0.34	0.91	1.25	1.62	1.26	0.92	3.7
Light labor, indoor	0.001	0.04	0.09	0.17	0.10	0.10	100
Annual clinical cases based on workforce distribution and exposures							
Fatal heat strokes, outdoor	629	1166	1444	1869	1499	870	
Fatal heat strokes, indoor	10	259	517	711	495	485	
Nonfatal strokes, outdoor	2221	4127	5071	6219	5145	2924	
Nonfatal strokes, indoor	356	1261	1940	2587	1940	1584	
Heat exhaustion, outdoor	886 551	1 653 717	2 025 222	2 489 478	2 056 143	1 169 592	
Heat exhaustion, indoor	139 301	498 691	778 091	1 029 054	768 551	629 250	
Years of healthy life lost; 30 years per fatality; 1 week per nonfatality; 1 day per heat exhaustion (240 work days per year)							
Fatalities	19 170	42 750	58 830	77 400	59 820	40 650	
Nonfatal heat strokes	52	108	140	176	142	90	
Heat exhaustion cases	4274	8969	11 680	14 661	11 770	7496	
Millions of work hours lost based on workforce distribution and exposures							
Heavy labor, outdoor	19 456	33 369	38 433	45 043	38 966	19 510	
Heavy labor, indoor	5494	14 340	19 555	25 049	19 648	14 154	
Moderate labor, outdoor	8529	15 992	19 723	23 987	20 096	11 567	
Moderate labor, indoor	1862	4656	7449	9312	7263	5401	
Millions of work years lost based on workforce distribution and exposures							
Heavy labor, outdoor	6.8	11.6	13.3	15.6	13.5	6.7	
Heavy labor, indoor	1.9	5.0	6.8	8.7	6.8	4.9	
Moderate labor, outdoor	3.0	5.6	6.8	8.3	7.0	4.0	
Moderate labor, indoor	0.6	1.6	2.6	3.2	2.5	1.9	

Working age population in 2050 is estimated at 768 million. Workforce distribution and exposures: agriculture, 24.1% (heavy labor, outdoor); industry, 42.1% (moderate labor, indoor); services, 33.8% (not affected).

Industries that are already operating should have budgets to have engineering controls, including providing mechanical aids for material handling – dollies, carts, lifting devices – to reduce physical activity need. As part of administrative controls, the health and safety policy should be geared to protecting the workers by training, awareness about the signs and symptoms of heat stress, and job rotation for hot environments and strenuous work.

Personal protection devices with local cool air fans, cooling vests, or other methods for personal cooling should also be considered, but in some situations the only feasible way to avoid overheating is to schedule sufficient rest periods in a cooler space. In some countries, thresholds for maximum heat at work are applied and workers can stop working while their pay is continued, as agreed between trade unions and employers (e.g., in Australia).

It should also be emphasized that this area of occupational health still requires more attention in research and development activities. The global Hothaps program aims at creating more evidence within many countries, in order to raise awareness and create local examples of how the increasing workplace heat exposure problems can be managed. In this sense, research becomes a part of the prevention efforts.

1.12.11 Conclusions

Climate variables are well-known hazards in occupational health, and the increasing heat levels that climate change on top of climate variability is projected by the IPCC to bring about are very important to consider in local, national, and global health programs. By using the WBGT level as the heat indicator, not only temperature but also other climate variables are incorporated into the analysis. Humidity is of particular importance.

This chapter indicates that there are a number of climate-related occupational health and work productivity concerns that can become of great importance depending on the location of workplaces. The most direct impacts are due to occupational heat stress. The authors' analysis indicates that such stress will become an increasing problem, primarily in tropical and subtropical areas. Research and analysis on vulnerability to increasing heat exposure as a result of anthropogenic climate change on top of natural climate variability need to take this part of the health risk panorama into account.

See also: Responding to Climate Change: Assessing Risks to Human Health and Healthcare system; What Have We Learned about Climate Variability and Human Health?; Extreme Weather Events; Recognizing and Reducing the Threats to Human Health and Environmental Ecosystems from Stratospheric Ozone Depletion; Sea-Level Rise and Health; Impact of Environmental Change on Ecosystem Services and Human Well-being in Africa; Precipitation and Flood Hazards: Health Effects, Risks, and Impacts; Environmental Migration and Population Displacements; Possible implications of Changing Climate Patterns on Water-Related Diseases; Food, Nutrition, and Public Health; Heat-Related Mortality; Climate, Urban Air Pollution, and Respiratory Allergy; Impact of HIV/AIDS Disease Burden Complex on Health and Environmental Resources in South Africa: Exploring Historical Perspectives, Linkages, Human-Ecosystem Interactions, Vulnerabilities, Policy and Adaptation Scenarios; Cold-Related Mortality and Morbidity; Vulnerable States: Pacific Island Countries; Vulnerability and Health: Exploring the Linkages in a Case Study from Southern Africa.

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New Heat Indicator UTCI Website: UTCI Universal Thermal Climate Index http://www.utci.org/.

1.13 Cold-Related Mortality and Morbidity

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1.13.1 Introduction

It has long been observed that many diseases exhibit seasonal variations and that the characteristics of climate may give rise to some of these patterns. Many parts of the world currently experience higher rates of mortality and morbidity during winter months than during the summer (Wyndham and Fellingham 1978). Part of this wintertime excess can be attributed to seasonal infections such as influenza, but epidemiologic studies have demonstrated that the biggest contribution is made by the explicit effects of exposure to low ambient temperatures (Wilkinson et al. 2004). In most cases, very few of these impacts will be as a direct result of hypothermia, but rather due to cardiovascular and respiratory problems (Goodwin 2007).

This chapter reviews physiologic and epidemiologic evidence of the health effects of wintertime weather. It identifies individual and contextual-level risk factors that heighten vulnerability to cold and provides evidence of adaptation measures that help to minimize impacts. The implications of current and future cold impacts for public health policy are also discussed.

1.13.1.1 Historical Context

Humans have a long history coping with wintertime weather. The period between the fourteenth and the nineteenth centuries became known as the Little Ice Age in Europe because of the severity of the climate. In England, frost fairs were often held on the river Thames in London because it froze over in very harsh winters. During the Great Frost of 1683–84, the worst frost recorded in England, the Thames was completely frozen for 2 months (Appleby 1980).

Historically, exposure to cold weather has been of much public and research interest because of the high wintertime burden on public health experienced in many countries and the annual pressures this places on the usage of health services. Studies conducted as far back as the nineteenth century have identified a detrimental effect of cold weather on human health (Farr 1885). The particular role of low temperatures was demonstrated using a variety of health end points throughout the early part of the twentieth century (Russell 1928; Holland et al. 1961; Loudon 1964). The most recent epidemiologic studies use powerful analytic techniques originally developed for air pollution epidemiology to disentangle the explicit effects of ambient temperature from circulating infections and other seasonal factors. Although there is evidence that adverse cold-related health impacts have been decreasing over many decades because of improvements in housing, better health care, and other factors (Carson et al. 2006; Barnett 2007; Donaldson and Keatinge 1997), the winter excess still remains high in many countries. Recent global increases in fuel prices are also likely to impact negatively on people's ability to warm their homes sufficiently during cold weather.

1.13.2 Cold-Related Health

1.13.2.1 Physiological Effects of Cold

When challenged by cold, the human body focuses on maintaining vital organs. The first response to cold is vasoconstriction,

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in which blood flow is reduced in the skin and extremities so as to reduce heat loss to the air and keep vital organs warm and oxygenated. Continued cooling induces muscle contractions, shivering, and rapid breathing. Cold air in the lungs may cause the bronchioles to constrict; the heart rate slows, but may increase in those with chronic heart disease.

Less than 1% of cold deaths are caused by a drop in core body temperature (hypothermia) (Collins 1987), whereas the bulk of cold deaths are due to stress to the body of maintaining core body temperature at less than the optimal indoor or outdoor temperatures, and subsequent cardiac and cerebrovascular responses. The difference in etiology is evidenced by the lagged effect of temperature, that is, deaths continue to occur in the days following a drop in outdoor temperature rather than only on the day the temperature drops. It has been reported that coronary deaths are at their highest a few days after exposure to cold weather, whereas respiratory deaths peak about 2 weeks following initial exposure (Keatinge 2002). Prolonged or chronic lower level cold stress causes an immune and inflammatory response. The blood pressure increases, along with fibrinogen, cholesterol, and platelet levels and red and white blood cell counts. Lung inflammation from cold air, possibly compounded by increased virus survival at cold temperatures, increases the risk of contracting respiratory infection (Maheswaran et al. 2004).

Table 1 summarizes the time course of physiologic responses to cold weather exposure.

1.13.2.2 Epidemiology Studies of Cold-Related Health

Epidemiology studies generally quantify two different measures of cold-related health. The first relates to assessment of the seasonal distribution of health events, and an excess winter effect is obtained by measuring the number of health events occurring in the winter months compared to at other times of the year. The second type quantifies the explicit effect of weather factors (mainly ambient temperature) by assessing changes in the daily number of health events in relation to day-to-day fluctuations in the weather. These studies are usually based on regression analysis of daily time-series data, or similar case-crossover designs, and only allow for assessment of acute effects (a few days or weeks) of cold weather exposure.

There are many more studies of the effects of cold, or winter season, on mortality than on morbidity outcomes, in part because mortality statistics are routinely collected in most countries. Descriptive studies of particular diseases sometimes report seasonal incidence – but only as incidental findings not usually discussed in the context of temperature-related health. The difference in all-cause hospitalization rates between different temperatures or seasons is smaller than with mortality. Within disease categories, some conditions can have a winter excess for mortality but a nonwinter excess for hospitalizations. For example, work from New Zealand showed that hospital admission rates for digestive conditions (ICD 10, Chapter 11) were lower in winter than during other months, but death rates were higher in winter (Telfar Barnard 2010). In other disease categories, the winter burden also varies: the excess winter index for circulatory illness (ICD 10, Chapter 9) is higher for deaths than for hospitalizations, while for respiratory disease, the index is higher for hospitalizations than for death.

Some studies also assess more indirect processes of cold exposure, for example, falls in the elderly are more common in the winter, not only because of winter injury hazards such as ice (Bulajic-Koplar 2000) but also because coordination is impaired by cold-reduced circulation.

1.13.2.2.1 Seasonal Distribution of Health Events

In most countries, mortality and morbidity rates are highest during the winter months. Some of this can be attributed to

Table 1 Immediate and delayed physiologic responses to cold exposure

Exposure/period	*Immediate*	*Hours*	*Days/weeks*	*Months*
Moderate cold exposure	Moderate vasoconstriction Increased blood pressure Can cause circulatory illness or death in those with compromised circulatory system	Reduced lung function, as measured by FEV_1 Lung inflammation Suppressed immune responses Can trigger asthma attacks, increases susceptibility to respiratory illness	Increased cholesterol Increased fibrinogen Increased white and red blood cell counts Increased platelet levels Further increased blood pressure More time indoors; if with other people increases exposure to infectious diseases	Decreased vitamin D levels Seasonal dietary changes may also reduce vitamin C
Extreme cold exposure	Vasoconstriction Muscle contractions Shivering Reduced heart rate in healthy adults, possible increase in heart rate among those with chronic heart disease Tacypnea (rapid breathing) Bronchoconstriction	Decreased breathing Cardiac arrhythmias Ventricular fibrillation Cardiac arrest Loss of consciousness Amnesic episodes Ischemic stroke	Death	

FEV_1, forced expiratory volume in 1 s.

seasonal infections such as influenza and other factors, but the largest contribution is from low temperatures. Figure 1 shows the fraction of deaths in the United Kingdom that is attributable to monthly variation, before and after adjustment for influenza and low temperature (Wilkinson et al. 2004).

Analyses of seasonal distributions of health events usually compare event rates in two divisions of the year, most commonly winter versus nonwinter or winter versus summer. The difference between the selected seasons is expressed as an index, where a value of 1 indicates no difference between seasons; a value greater than 1, a winter excess; and a value less than 1, a summer/nonwinter excess. The most common metric used is Curwen's Excess Winter Mortality Index, which is calculated as the average deaths per day in the four coldest months (Dec., Jan., Feb., Mar. for the northern hemisphere and Jun., Jul., Aug., Sep. for the southern hemisphere) minus the average deaths per day over the warmer months divided by the average deaths per day over the warmer months. The formula for the northern hemisphere is as follows:

$$\frac{\frac{\sum_{\text{deaths}}[\text{Dec., Jan., Feb., Mar.}]}{121} - \frac{\sum_{\text{deaths}}[\text{Aug., Sep., Oct., Nov., Apr., May, Jun., Jul.,}]}{244}}{\frac{\sum_{\text{deaths}}[\text{Aug., Sep., Oct., Nov., Apr., May, Jun., Jul.,}]}{245}}$$

Alternatively, the annual distribution of deaths may be modeled as a sinusoidal curve, with the differences in deaths between one season and another measured as, for example, the difference between the top and the bottom of the curve, or alternatively the difference between the middle and the top of the curve.

Seasonal indices have the advantage of including health events due to longer term seasonal effects and can be used to calculate an estimated number of 'excess winter deaths,' which may provide a metric more meaningful to a lay audience.

Studies comparing excess winter mortality levels in different countries have found that New Zealand has a large excess and that within Europe, Portugal, Ireland, and the United Kingdom also carry a high burden (McKee 1989; Curwen et al. 1997). However, some of the low excesses observed in cold Scandinavian countries may be due to the use of arbitrary seasonal definitions (Wilson et al. 2001). Ascribing season based on calendar date is somewhat arbitrary, but assigning season in any other way complicates interannual comparisons.

Regardless of temperatures, winter mortality excesses may also be high in years experiencing major influenza epidemics. In addition, year to year changes in seasonal indices and absolute 'excess winter death' numbers are not ideal for measuring the future impact of climate, as increasing heat-related impacts in the comparison months may mean that a winter mortality index ostensibly reduces even if the true wintertime burden remains the same.

1.13.2.2.2 Studies Assessing Explicit Weather Factors

The acute relationship between health events and climate variables is most commonly estimated using regression analysis of time-series data measured over a period of a few years. These studies control for time trends and broad seasonal patterns, and also usually for time-varying confounders such as circulating infections and air pollution concentrations. The most commonly characterized relationship is that between the daily number of deaths and the daily ambient temperature measurements in any particular setting.

In many settings, mortality levels rise in a smooth, often linear, manner in relation to a fall in temperatures during winter months. This risk is sometimes referred to as the cold slope, and the steepness of the slope may vary across cities and countries depending on differing climatic, demographic, and socioeconomic profiles (Analitis et al. 2008).

One key consideration in the assessment of cold risk is that cold effects can be delayed by a few days or weeks following initial exposure. The effects of exposure may, therefore, be distributed across many subsequent days of mortality counts, thus leading to the need of studies of this type to simultaneously model exposure effects over multiple days. Such a distributed lag curve is shown for various outcomes in 15 European cities combined in Figure 2 (Analitis et al. 2008). It can be seen that the effect of cold on cardiovascular disease (CVD) deaths peaks a few days following exposure and then reduces to zero effect, whereas the respiratory deaths are much longer sustained. For each outcome, summing the effects of the individual lags provides a total effect of short-term exposure to low temperatures.

1.13.3 Risk Factors for Cold-Related Mortality and Morbidity

A person's susceptibility to cold weather is affected by both individual and contextual risk factors (Conlon et al. 2011).

1.13.3.1 Individual-Level Risk Factors

1.13.3.1.1 Age

While all people are susceptible to cold, some groups are more vulnerable than others. The most important risk factor for cold-induced illness and death is age, with the elderly and very young being at highest risk. While evidence for increased risk between middle and third age is occasionally mixed, studies of both mortality and morbidity universally find those aged over 60 years to be at greater risk than younger

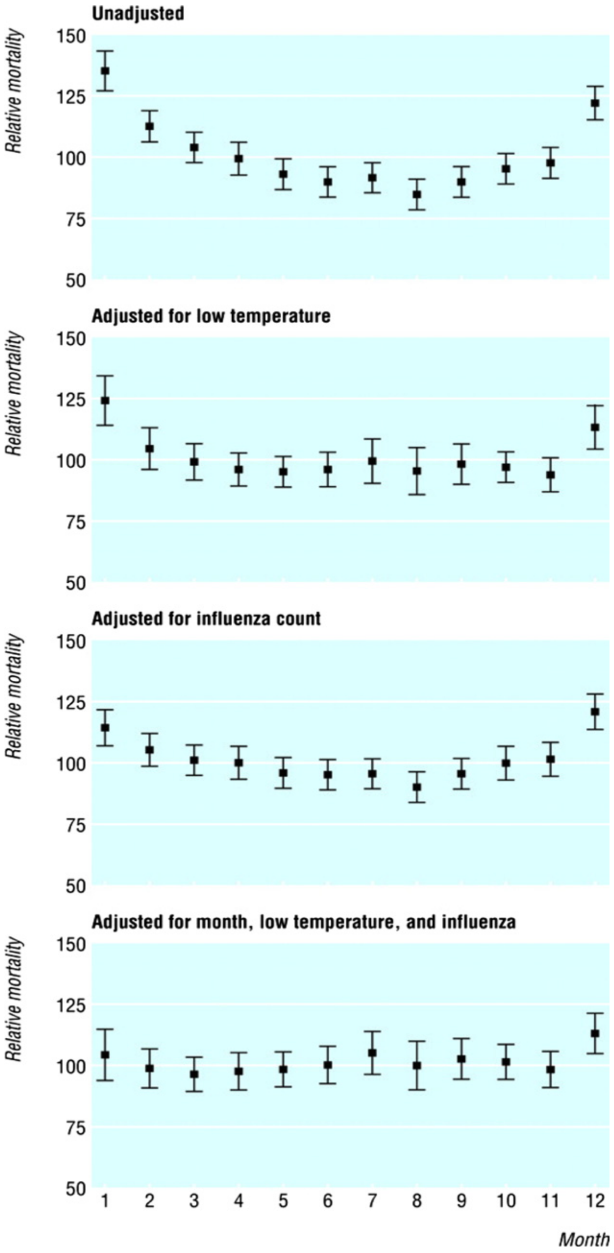

Figure 1 Fraction of deaths attributable to monthly variation. Reproduced from Wilkinson, P., S. Pattenden, B. Armstrong, A. Fletcher, R. S. Kovats, P. Mangtani et al., 2004: Vulnerability to winter mortality in elderly people in Britain: population based study. *BMJ*, **329** (7467), 647, Epub 2004/08/19.

adults and those under 5 years of age to be at greater risk than older children and young adults (Gemmell et al. 2000; Davie et al. 2007).

1.13.3.1.2 Preexisting Illness

Excess winter mortality and morbidity indices are higher for chronic respiratory and cardiovascular conditions, that is, chronic obstructive pulmonary disease (COPD), asthma, and chronic heart disease.

1.13.3.1.3 Sex

Women are generally found to be more susceptible to the effects of cold than men, at all ages (Keatinge 2002; Davie et al. 2007; Stewart et al. 2002). However, Curwen found no difference between over-45-year-old men and women between 1968 and 1985 in Britain. In the Czech Republic, mortality risk during cold spells was most pronounced in middle-aged men (Kysely et al. 2009).

1.13.3.1.4 Ethnicity

The presence or otherwise of differences in cold-impact by ethnicity is underinvestigated. While there are seasonal differences in vitamin D levels by ethnicity, studies in New Zealand have found no difference in excess winter mortality between Europeans and Maori or Pacific people in New Zealand (Telfar Barnard 2010; Davie et al. 2007) but excess hospitalizations were higher in winter for both groups (Telfar Barnard 2010). However, in the United Kingdom, Rudge and Gilchrist (2007) found that census enumeration districts with a higher percentage of white pensioners had higher winter counts of respiratory hospitalizations. An early South African study found differences in seasonal mortality distribution between 1968 and 1971 by ethnicity, but these differences were accounted for by higher rates of summer infant mortality due to gastroenteritis among nonwhite groups (Wyndham and Fellingham 1978). Among adults in seven US cities, cold effects were reported to be higher in blacks compared to whites (O'Neill et al. 2003).

1.13.3.2 Contextual Risk Factors

1.13.3.2.1 Socioeconomic Status

There is still debate over the degree to which socioeconomic status exacerbates or increases risks of cold exposure. Hales et al. (2010) found that those in the lowest income tertile in New Zealand had a 13% (95% confidence interval (CI) 8–19%) higher risk of winter death than those in the highest tertile. The strongest associations were seen for infectious diseases. Cold-related mortality risk in Sao Paulo, Brazil, was not found to be modified by area-level markers of socioeconomic position (Gouveia et al. 2003).

1.13.3.2.2 Rurality

The evidence for differences in effects of cold by rurality is varied or inconclusive. In the United Kingdom, excess winter mortality has not been found to vary by population density (Lawlor et al. 2002), although living in a rural area may increase the effect of socioeconomic deprivation (Hajat et al. 2007). On the contrary, two New Zealand studies have found urban dwellers to be at significantly increased risk of excess winter health events (Telfar Barnard 2010; Hales et al. 2010). A spatial analysis of temperature extremes in Taiwan found greater vulnerability in rural areas compared to metropolitan regions (Wu et al. 2011).

1.13.3.2.3 Housing

The evidence implicating poor housing in cold-related mortality or morbidity is mixed (Barnard et al. 2008). Ecological evidence tends to show no effect; individual-level

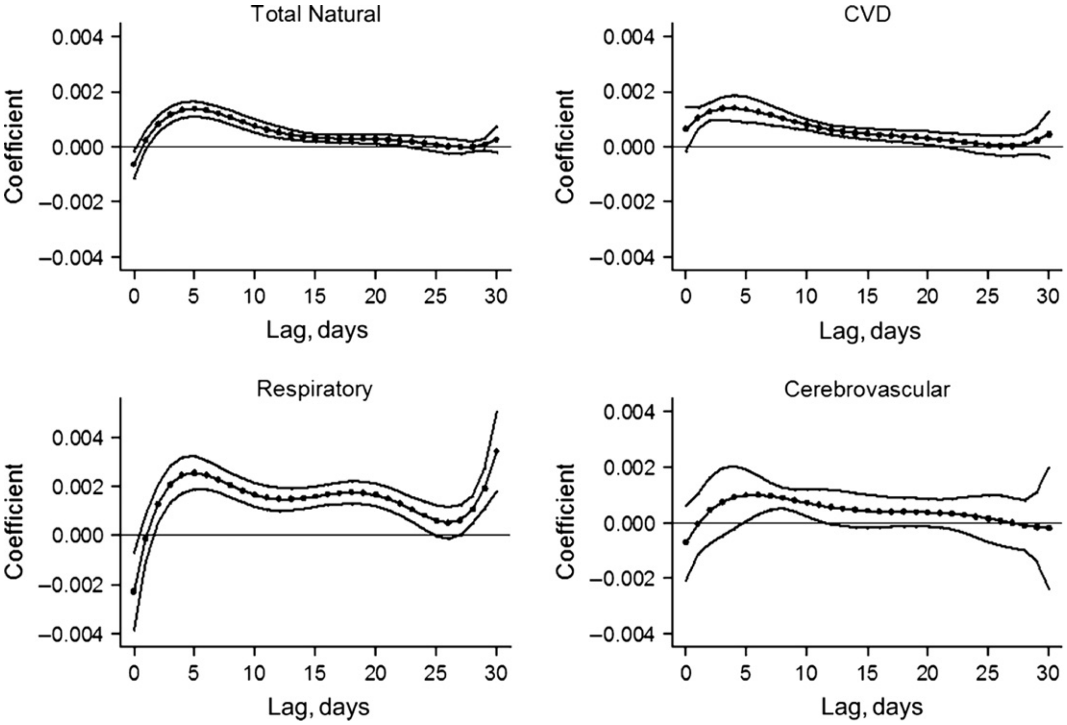

Figure 2 Distributed lag curves (and 95% confidence intervals) up to 30 days of the effect of a 1 °C lower apparent temperature on daily number of deaths, all ages, during the cold season (Oct.–Mar.), 1990–2000. Reproduced from Analitis, A., K. Katsouyanni, A. Biggeri, M. Baccini, B. Forsberg, L. Bisanti, et al., 2008: Effects of cold weather on mortality: results from 15 European cities within the PHEWE project. *Am. J. Epidemiol.*, **168** (12), 1397–408, Epub 2008/10/28.

studies show some effect, with indoor temperature being more important than other housing indicators such as dwelling age or presence of central heating. Tenure may also make a difference: New Zealanders living in rented accommodation were at greater risk of winter death than home owners (odds ratio 1.05 (95% CI 1.01–1.10)) (Hales et al. 2010).

1.13.3.2.4 Household Crowding

We were unable to find any studies that measured the effect of household crowding on cold-related health events, but as household crowding is generally found to contribute to increased risk of respiratory infection (Cardoso et al. 2004) and respiratory infections make up a large percentage of winter health events, household crowding may contribute to the winter health burden.

1.13.4 Adaptations

The fact that wintertime health impacts are not necessarily largest in the coldest countries indicates that adverse cold-related health events are largely avoidable and that adaptations to cold weather will play a key role in determining current and future cold-related health burdens.

At an individual level, human adaptation to cold weather can not only be physiological but also due to changes in behavioral responses. Some short-term physiological adaptation to cold can be achieved within 2 weeks of exposure (Rintamaki 2007). Thermoregulatory responses to cold are either insulative (e.g., circulatory adjustments) or metabolic (shivering) (Makinen 2010). Most experimental evidence on physiologic responses to cold exposure is based on studies conducted on healthy individuals in sports and military settings. However, a person's ability to thermoregulate adequately is affected by factors such as fitness, body composition, underlying health status, and age. Elderly people are most vulnerable to cold exposure, in part due to a reduced ability to retain body heat. Children also can lose heat quickly because of a higher surface area ratio compared to adults; however, this may be partially offset by a higher metabolic rate (McCullough et al. 2009).

Differences in behavior are likely to explain much of the variation in cold risk observed between countries. In general, cold weather-related health burdens tend to be largest in countries that experience mild winters, whereas countries that are used to harsh winters and are well adapted to them have lower risk. This indicates that relative temperature levels are more important than absolute values in determining health risks. A study conducted in one of the world's coldest cities – Yakutsk, in Eastern Siberia – found that all-cause mortality and mortality specifically due to ischemic heart disease and stroke did not rise as outdoor temperatures fell to −48.2 °C (Donaldson et al. 1998). Those surveyed in this study reported wearing very warm clothing during the winter and staying indoors in warm housing when the weather became extremely cold. Another study comparing European regions observed that the mortality risk was greatest in regions with warm winters, in populations with cooler homes, among people who did not regularly wear hats, gloves, and anoraks and were less active outdoors (Cold exposure and winter 1997).

One of the key contextual ways that societies can adapt to cold weather is through the built environment, especially housing. Internal temperatures of a person's home contribute greatly to overall exposure to cold. In many countries, people spend more than 90% of their time indoors, mostly in their own homes. (Chapman et al. 2009). The insulation of homes in low-income communities in New Zealand led to improvements in various health outcomes among occupants, although these were all based on self-reported measures (Howden-Chapman et al. 2007). In a follow-up to this study, no improvements were found in clinical measures of lung function among asthmatic children in the insulated homes, although improvements were observed based on self-reported measures (Howden-Chapman et al. 2008). A cost–benefit analysis of this insulation program concluded that the total monetary values in health gains and in energy and greenhouse gas emissions savings in these homes was 1.5–2 times greater than the cost of retrofitting the insulation (Chapman et al. 2009). In general, the link between housing quality and wintertime health is still inconclusive (Barnard et al. 2008).

One specific factor that has been linked to cold risk and housing is a lack of affordable warmth, also known as fuel poverty. In the United Kingdom, households that require 10% or more of their income to achieve adequate warmth in the home are classified as being in fuel poverty (Sefton and Chesshire 2005). In England, 12% of households were fuel poor in 2006 and the rate was double in Scotland (Liddell and Morris 2010). **Figure 3** shows the percentage of fuel-poor households in England, by type of occupant (DoEaCC 2010). About half of the people in fuel poverty in England are over 60 years of age.

Interviews of occupants in households who had benefited from the Warm Front scheme (a government initiative aimed at alleviating fuel poverty in England by improving home heating) found that recipients reported improved perceptions of physical health and comfort, especially of mental health and emotional well-being (Gilbertson et al. 2006). There were also reports of improved family relations and greater use of kitchens and better nutrition. However, heating bills were not substantially lower. A recent comprehensive review of fuel poverty and human health concluded that there is little evidence to date of physical health improvements in adults receiving fuel poverty interventions, although their *perceptions* of well-being were improved and physical health gains among children were more evident (Liddell and Morris 2010).

Although most evidence to date on cold impacts comes from high-income settings, reducing global burdens will require greater identification of vulnerable groups in other settings and feasible options for interventions, such as in rural Bangladesh (Hashizume et al. 2009). The introduction of energy-efficient measures also has the potential for other health impacts, both positive and negative – for example, changes in home ventilation could have adverse health impacts as a result of increased exposure to indoor pollutants (Wilkinson et al. 2009). In low-income countries, the current use of biofuels for domestic cooking and heating can lead to exceptionally high levels of exposure to some pollutants.

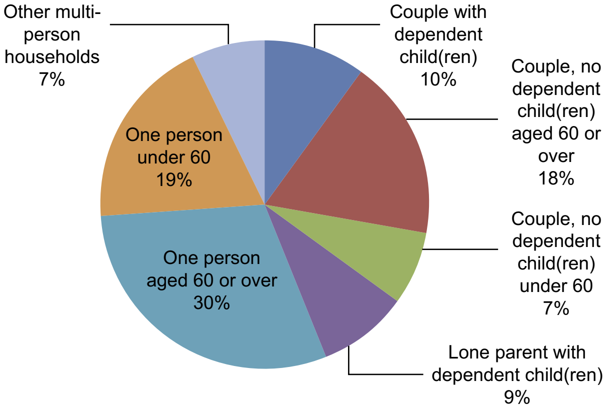

Figure 3 Fuel-poor households by type of occupant in England in 2009. [Available online at http://www.decc.gov.uk/assets/decc/11/stats/fuel-poverty/5270-annual-report-fuel-poverty-stats-2012.pdf.]

1.13.5 Implications of Public Health Policy

Some countries now have policies to minimize cold-related health impacts on public health. In many cases, these relate to strategies to improve housing conditions for vulnerable members of society. The UK Fuel Poverty Strategy seeks to eradicate fuel poverty by 2018, first by targeting three vulnerable groups: people aged over 60 years, those with disabilities or long-term illness, and families with children; in the second phase, nonvulnerable groups will be prioritized (BERR 2001). Such strategies may also require better measurement of what constitutes fuel poverty (Hills 2011).

In some countries, governments are now introducing integrated cold weather response plans which besides planning long-term intervention strategies also trigger acute intervention measures. Since the winter of 2011, England has had in operation a cold weather plan run by the Department of Health (DH 2011). The plan provides advice for individuals, communities, and agencies on how to prepare for and respond to severe cold weather and initiates acute actions by health and social care professionals and other community organizations to strengthen the protection and support of vulnerable individuals when cold weather is forecast.

The advice that is given to vulnerable individuals in such plans should consider the potentially sensitive nature of categorizing a person as being high risk. A recent qualitative study concluded that practices and devices strongly recommended to older people and past generations tend to be heavily stigmatized, leading to resistance from individuals to follow age-related advice (Day and Hitchings 2011).

Although most policy actions relate to keeping houses warmer during winter, exposure to cold outside of the home is also important (Keatinge and Donaldson 2004). The DH cold weather plan provides guidance to individuals not only on keeping warm at home but also on activities and clothing when outdoors. It has been suggested that measures such as windproofing bus shelters and better heating of waiting rooms could reduce the cold burden further (Keatinge and Donaldson 2004).

Also, in the United Kingdom, the Government weather service, the Met Office, has in place a health forecasting system, whereby weekly risk predictions for emergency hospital admissions for COPD are provided to participating hospitals to aid clinical management. The risks are based on models combining weather forecasts with information on infectious disease activity and other seasonal parameters.

Globally, the World Health Organization supports national authorities in developing and revising cold weather plans in order to promote public health preparedness during winter and cold weather (World Health Organization 2012). They stress that preparedness plans should be implemented in coordination with other sectors – such as housing, energy, transport, and education.

1.13.6 Conclusions

Although concerns about global warming have recently focused on the dangers of exposure to hot weather, cold-related exposure remains a substantial public health problem in many parts of the world. This may be exacerbated by recent global increases in fuel prices, leading to a greater inability among people to warm their homes adequately during cold weather. Intervention measures designed to minimize cold exposure and reduce fuel poverty will play a key role in determining current and future health burdens due to cold weather.

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Met Office health forecasting service – http://www.metoffice.gov.uk/health/public

World Health Organization – http://www.euro.who.int/en/what-we-do/health-topics/emergencies/disaster-preparedness-and-response/news/news/2012/02/health-services-must-prepare-for-extremely-cold-weather.

1.14 Vulnerable States: Pacific Island Countries

E Hanna

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Glossary

Adaptation Adaptation to climate change is the adjustment of a system to moderate the impacts of climate change to take advantages of new opportunities or to cope with the consequences (Adger et al. 2003).

Adaptive capacity The ability of a system to adjust to climate change (including climate variability and extremes), to moderate potential damage, to take advantage of opportunities, or to cope with the consequences (IPCC 2007b). Adaptive capacity is shaped by available resources, institutions, and skills and knowledge among others.

Climate Usually defined as the average weather, or more rigorously as the statistical description in terms of the mean and variability of weather (surface variables such as temperature, precipitation, and wind), over a period ranging from months to thousands or millions of years. The classical period is 30 years, as defined by the World Meteorological Organization (WMO) (IPCC 2007b). An alternative definition is the system consisting of the atmosphere, hydrosphere, lithosphere, and biosphere determining the Earth's climate as the result of mutual interactions and responses to external influences (forcing). Physical, chemical, and biological processes are involved in interactions among the components of the climate system (NRC 2005), AMS. Dominant natural forcings are solar and volcanic action.

Climate change according to the UNFCC A change of climate that is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and that in addition to natural climate variability is observed over comparable time periods (UNFCCC 1994). Such factors include increased greenhouse gas (GHG) concentrations associated with fossil fuel burning, sulfate aerosols produced as an industrial by-product, ozone (stratospheric and tropospheric), and human-induced changes in land surface properties.

Coping capacity The manner in which people, organizations, and societies use existing resources to achieve various beneficial ends during and immediately after unusual, abnormal, and adverse conditions of a disaster event or process. Strengthening of coping capacities can build resilience to withstand the effects of future natural and other hazards.

Coping strategies Short-term actions to ward off immediate risk, rather than to adjust to continuous or permanent threats or changes. Coping strategies are 'first-resort' responses, and can become part of the 'repertoire' of behavior to also be used to respond to recurrent problems. Note, as directed at immediacy, they are not necessarily well targeted as a long-term strategy, so when used as a response to stress, it is possible that vulnerability may increase in the long term (Schipper et al. 2008).

Ecosystem The sum of the living organisms in an area and nonliving chemical and physical factors with which those organisms interact. *Healthy ecosystems* provide a variety of services to humans, most obviously providing food, water, and shelter, in addition to life-supporting functions by purifying air and water, nutrient cycling, and detoxification and decomposition of wastes.

Hazard A potentially damaging physical event, phenomenon, or human activity that may cause the loss of life, injury, property damage, social and economic disruption, or environmental degradation (ISDR Scientific and Technical Committee 2009).

Health determinants Certain upstream or distant factors have great potential to impact on public health, even though these exposures are far apart in time or space from the witnessed ill-effects relates. Determinants of health include policies, for example, those that drive current levels of population growth, consumption, and waste issues and the uses of technology.

Maladaptation An action or process that increases vulnerability to climate change-related hazards. Maladaptive actions and processes often include planned development policies and measures that deliver short-term gains but lead to exacerbated vulnerability in the medium to long term (UNDP 2011).

Micronutrients Essential dietary elements (vitamins and minerals) that are needed only in very small quantities. They include copper, zinc, selenium, iodine, magnesium, iron, cobalt, and chromium and vitamin A. Micronutrient deficiency is a lack of one or more essential vitamins or minerals such as vitamin A, iron, or zinc.

Resilience The ability of a social–ecological system to absorb disturbances without losing its fundamental structure and function (combination of definitions).

Risk The probability of harmful consequences, or expected losses (deaths, injuries, disease, property, disrupted livelihoods or economic activity, environmental damage) resulting from interactions between natural or human-induced hazards and vulnerable conditions. Conventionally, risk is expressed by the notation Risk = Hazards × Vulnerability.

Social determinants of health The social determinants of health are the conditions in which people are born, grow, live, work, and age, including the health system. These circumstances are shaped by the distribution of money, power, and resources at global, national, and local levels, which are themselves influenced by policy choices. The social determinants of health are mostly responsible for health inequities – the unfair and avoidable differences in health status seen within and between countries.

Stunting When children are too short for their age – as a result of chronic malnutrition.

Undernutrition Exists in several forms: stunting, wasting, or micronutrient deficiency (see definitions in this section) Causes include inadequate diet and infection, and it is usually associated with a lack of access to sufficient quantities of nutritious food, clean water, sanitation, or health care.

Vulnerability In the context of climate change, vulnerability is the degree to which a system is susceptible to, and unable to cope with, perturbations or stress associated with climate change, including climate variability and extremes. Vulnerability to climate change is a function of (1) the character, magnitude, and rate of climate stress, and the variation to which a system is exposed; (2) its sensitivity to these factors; and (3) its capacity to recover from, or fundamentally adapt to, these influences.

Wasting When children are too light for their height – as a result of acute malnutrition.

Weather Unlike *climate*, which is long-term phenomenon, weather is a short-term (minutes to weeks) phenomenon, describing atmosphere, ocean, and land conditions hourly or daily. Weather is not constant. It is dynamic and always changing. Weather is the day-to-day state of the atmosphere, measured and recorded in terms of temperature, humidity, precipitation, cloudiness, visibility and wind, and their short-term variation (WMO and a combination of definitions).

1.14.1 Introduction

> “Climate change is among the most serious challenges facing Pacific Island countries and territories, threatening every aspect of their environment, social and economic development, and political and human security. The nature of these small countries – often sparsely populated atolls in a vast ocean – makes them highly vulnerable to the projected effects of climate change. For some of the 22 member countries and territories of the Pacific Community, it is a question of survival, and for all of them, a time for action.”
>
> Commonwealth Health Ministers’ Update 2009 (Rodgers et al. 2009).

The relationship between climate change and human health is enmeshed in a complex web of interlinked and overlapping pathways. Direct impacts of climate on human health can be readily seen, most notably in extreme events. These are immediate and often dramatic, and these events feature widely on international news media, in the form of broad-scale disasters wreaking havoc on hapless populations. Indirect effects arising from these extremes, increasing climate variability, or indeed slow shifts in climate patterns are often more insidious in their action and more entrenched as they interfere with basic necessities of life that are fundamental to human health and well-being. From the community’s standpoint, effects of climate change can arise through different pathways, such as via interruptions to ecosystems or fragmentation of sociocultural and economic infrastructure. Effects become insidious when they act in concert and create a multiplying effect that further reduces resilience to climate extremes and existing social challenges, thereby deepening vulnerability and entrenching long-term disadvantage.

Not all effects of perturbations in climate systems would be deleterious to human health and well-being. In certain circumstances, there would be some positives; however, the global net impact is predicted to be negative (Nicholls 2011) and not evenly distributed between regions, countries, or subpopulations within countries. ‘Communities,’ in this chapter, can be regional (e.g., Mediterranean, African), national (e.g., Sudanese, Tongans), or subgroups (e.g., farmers, children, or the socioeconomically disadvantaged).

One clear example of a climate change benefit exists for communities from cool countries, such as the United Kingdom, where warming is likely to result in a net reduction in temperature-related deaths. By the 2020s, 2050s, and 2080s, premature deaths are estimated to reduce by approximately 15%, 30%, and 45%, respectively. Owing to the current high numbers of annual cold deaths (estimated between 26 000 and 57 000 per year), this health gain outweighs the estimated 60% increase in heat-related morbidity in the near term (2020s), and approximates 200% increase in the medium term (2050s), based on the medium emissions scenario, central estimates. However, this benefit noticeably narrows by the 2080s (DEFRA UK 2012). This is not to suggest that the overall impact for the United Kingdom would be beneficial. The *UK Climate Change Risk Assessment 2012 Evidence Report* concludes that the combined effect of all the manifestations of climate change will bring a net deterioration. It is pertinent therefore for the public health effort to focus on the *health threats* arising from global warming and increasing climate variability and to assess what strategies are required to minimize health harm. This chapter will primarily address health threats among highly vulnerable communities and the mechanisms underpinning vulnerability to climate change.

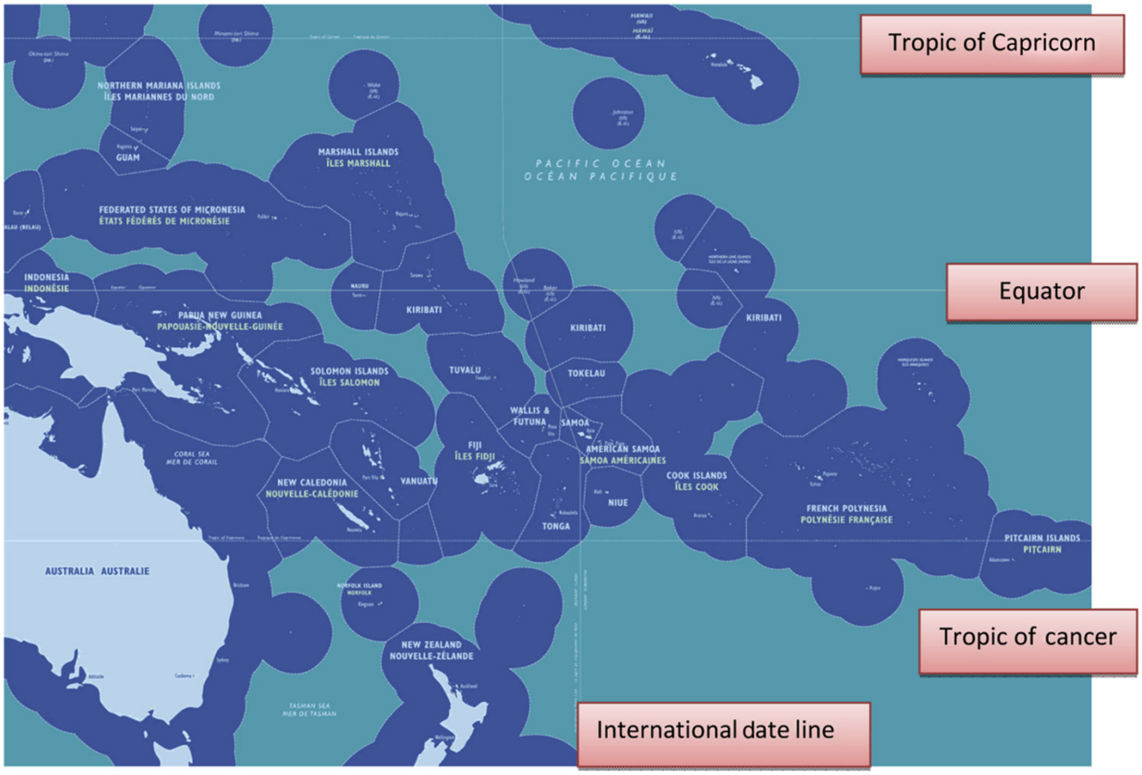
Tracking the various vulnerability pathways highlights the special needs of vulnerable communities and is key to understanding both the complexity and the urgency of action required. When examining the problem from a multi-perspective approach, it becomes readily apparent that attacking complex problems with singular linear responses is unlikely to make significant inroads. In this chapter, vulnerability to climate change is examined through the lens of food insecurity and multigenerational disadvantage. Food insecurity has been predicted to emerge as a global climate change risk, striking first on already vulnerable communities. Small Island Developing States (SIDS) are considered especially vulnerable to the net effects of global warming and increasing climate variability. Pacific Island countries provide a useful case study to demonstrate the interaction of complexities involved and to illustrate the pervasiveness of flow-on vulnerability effects that can reduce resilience in future generations.

The states that comprise the Pacific Island Countries and Territories (PICTs) lying south of the Tropic of Cancer are traditionally aggregated into three major groups: Melanesia, Polynesia, and Micronesia – reflecting the diverse geography, culture, and ethnic backgrounds of the indigenous inhabitants of the islands. This chapter will refer to those 22 PICTs served by the Secretariat of the Pacific Community (SPC).

- Melanesia (*black islands*) include Papua New Guinea (PNG), New Caledonia, Torres Strait Islands, Vanuatu, Fiji, and the Solomon Islands, plus some Indonesian provinces.
- Micronesia (*small islands*) lie mostly north of the Equator and include the Federated States of Micronesia (FSM), Marshall Islands, the Marianas, Kiribati, Nauru, Guam, Wake Island, and Palau.
- Polynesia (*many islands*) cover the largest area and include Tonga, Samoa, Tuvalu, American Samoa, Samoa, Cook Islands, Pitcairn Islands, Tokelau, New Caledonia, Niue, French Polynesia, Wallis, and Fortuna.

Although many similarities are shared by these 22 PICTs, country geomorphology and sociogeopolitical features vary greatly. However, governments of these three Pacific Island regions agree that climate change poses a serious threat to all small island states and coastal populations (Secretariat of the Pacific Regional Environment Programme (SPREP) 2011; WHO Western Pacific Regional Office & SPC 2009). Our discussion does not consider Australia and New Zealand as small Pacific Islands.

The SPC receives financial support from France, Australia, New Zealand, and the United States to assist these PICTs achieve their development goals.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OCÉAN PACIFIQUE
FEDERATED STATES OF MICRONESIA
ÉTATS FÉDÉRÉS DE MICRONÉSIE
INDONESIA
INDONÉSIE
NAURU
KIRIBATI
PAPUA NEW GUINEA
PAPOUASIE-NOUVELLE-GUINÉE
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SOLOMON ISLANDS
ÎLES SALOMON
TUVALU
TOKELAU
WALLIS & FUTUNA
SAMOA
FIJI
ÎLES FIDJI
AMERICAN SAMOA
SAMOA AMÉRICAINES
CORAL SEA
MER DE CORAIL
NEW CALEDONIA
NOUVELLE-CALÉDONIE
VANUATU
COOK ISLANDS
ÎLES COOK
NIUE
TONGA
FRENCH POLYNESIA
POLYNÉSIE FRANÇAISE
PITCAIRN ISLANDS
PITCAIRN
AUSTRALIA AUSTRALIE
NORFOLK ISLAND
NORFOLK
NEW ZEALAND
NOUVELLE-ZÉLANDE
TASMAN SEA
MER DE TASMAN

Source: Secretariat of the Pacific Community (Country profiles and health details on the 22 PICTs can be found on the SPC website: http://www.spc.int/en/about-spc/members.html or on the WHO website at http://www.wpro.who.int/countries/en/).

1.14.2 Climate Change: Determinants of Vulnerability

The World Meteorological Organization (WMO) defines a region's climate as the pattern of weather occurring over a 30-year period. As weather varies daily, climate is also variable. In human relevant time spans, a region's weather patterns will most commonly vary within a defined range, and this range oscillates seasonally yet within a broader envelope according to cycles driven by the influence of large systems such as the tropical multidecadal signal and the El Niño-Southern Oscillation (ENSO). ENSO is particularly significant in determining weather patterns across the Pacific Ocean. (The Earth's climate has also cycled through ice ages, and interglacial warm periods over longer frames of 100 000 years or so.) Stepwise shifts occasionally do occur, such as the one that occurred in the repeated dry periods at about 2000-year intervals in the Sahara during the Holocene (Mercuri et al. 2011), and there are more recent examples such as the recent halving of the rainfall in southwest western Australia (Bates et al. 2008; Timbal et al. 2006). Both are thought to be in response to anthropogenic landuse activities. Most weather that we observe occurs within the boundaries of these short-term cycles, which serve to define a region's climate, and a shift outside the boundaries indicates that the climate has changed. The IPCC defines 'climate change' as a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer. The persistence and time frame are critical to detect real shifts over and above the routine variation in weather.

Extreme weather events are defined as the occurrence of a value of a weather or a climate variable that falls above (or below) a threshold value near the upper (or lower) end of the range of observed values of the variable. Weather extremes fall at either tail of the distribution curve, and new weather records are set when extremes occur beyond the past recorded level. Historically, records are broken relatively infrequently and usually, only by small margins, which means the new record lies just a small margin *outside* the previous known extreme. Globally, the rate of weather records being broken has increased, and records are being broken by unusually large margins (Coumou and Rahmstorf 2012; Nicholls 2009). This increase in extremes is consistent with an increasing variability, as predicted by climate models, and suggests that a change in climate is underway.

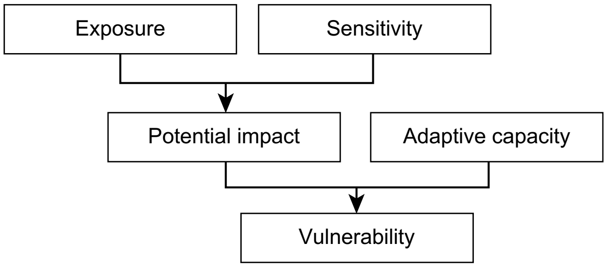

Figure 1 Components of vulnerability. Adapted from Schroeter D and the ATEAM Consortium, 2004: Global Change Vulnerability – Assessing the European Human-environment System: Potsdam Institute for Climate Impact Research.

Vulnerability to climate change is defined by the IPCC as "the degree to which a community, individual, or the environment is susceptible to and unable to cope with adverse effects of climate change" (UNFCCC 2011). In the context of human health, there are four determinants of vulnerability that need to be considered: exposure, sensitivity, potential impact, and adaptive capacity. **Figure 1** is often used to depict how these various forces interlink to construct a situation of vulnerability.

All countries are *exposed* to climate perturbations arising from their climate extremes, but how they are exposed to increasing climate variability as part of a changing climate will differ spatially and in type and intensity. Exposure intensity is a measure of the degree of climate extremes occurring, such as the temperatures reached and the duration of heat waves, the wind speeds of typhoons, the amount of rainfall over a given period, the length of drought, or the depth of floods. Alternatively, a significant deviation from the climate norm can constitute high-level exposure without the occurrence of extreme events, for example, a climate shift to a new state where the local ecosystems can no longer thrive. Plants evolve within a climate and require established patterns, such as cold nights or frosts, to complete their annual cycle. Total annual rainfall may remain relatively constant, but may shift between seasons, away from germination or peak growing times, and fall instead when harvest is due, or may shift toward fewer but heavier precipitation events. In this scenario, less rain seeps into the ground. Soil moisture is depleted to create drought-like conditions, which compromises agricultural yield, livelihoods, and food supply (IPCC 2008).

Sensitivity, as the name implies, relates to the susceptibility of the system to the exposure. Plants sensitive to temperatures include those that need frosts to generate bud burst and those that suffer leaf burn in frosts. Low-lying atolls, such as those in the Pacific, are highly sensitive to storm sea surges, as they have little protection from inundation that can introduce salty water in the water lens or salinate the soil. In relation to health, humans can tolerate a very narrow range in their core temperature (Hanna et al. 2011); we are sensitive to exposure to extreme heat and cold.

Combining the effects of exposure and sensitivity produces the *potential impact*. Using the above examples, atoll nations situated in the tropics are therefore exposed to strong tropical storms. Atolls are low lying and are highly sensitive to ecosystem interruption and infrastructure damage by big waves. Warm oceans generate strong cyclones or typhoons that in turn generate high seas and storm surges, and therefore, the potential impact for low-lying areas such as atolls from continued warming of the oceans is extremely high. Although episodes of low cyclonic activity continue to occur, notably during La Niña cycles, they are predicted to increase in intensity with climate change (Australian Bureau of Meteorology and CSIRO 2011b).

Countries with high *adaptive capacity* are better able to withstand climate extremes. Coastal mangroves help dissipate storm sea surges and minimize damage; hence a natural abundance or protection of native mangroves offers natural protection for low-lying lands. In the absence of mangroves, erection of sea walls can assist in deflecting storm surges to protect coastal areas; however, these are costly and require financial investment. Countries with sufficient elevated land can consider relocating low-lying populations to higher ground. These examples illustrate how adaptive capacity can take the form of *having options* to avoid or militate against the risk and *taking up options* such as building sea walls to protect against storm surges.

Technology and infrastructure can significantly contribute to the array of available options to help minimize harm. For example, weather warning systems (Paul 2009) and health care systems that effectively reach vulnerable community members may offer protection. Having technical knowledge and financial resources to identify and implement options provides a degree of protection from the potential impact of climate change. However, nontechnical solutions are also important. Strong social networks and access to traditional elders' knowledge provide support to communities in stress and boost resilience and have been the historical cornerstone of survival against previous climatic challenges. Also critical to success is the willingness to engage in adaptation at the national, community, and personal levels, as many barriers to adaptation are social in origin (Jones 2010).

Adaptive capacity is, however, constrained in countries that lack access to sufficient technical, human, and financial resources or that have limited (or lost) local knowledge, limited social services, or limited suitable infrastructure and flexible systems. Populations with only few options available to them have limited capacity to successfully avoid harm. Furthermore, their postdisaster recovery can be slow. Climate-induced natural disasters have been shown to delay progress toward achieving Millennium Development Goals (MDGs) by a decade or more (UNESCAP 2011).

To bring all these together, *vulnerability* is first a function of the degree of population or individual's exposure to significant changes in climatic variables and the sensitivity to these climatic variables, which combined, generate the potential impact. Adaptive capacity then moderates that potential impact to determine the actual residual vulnerability.

It is important to recognize that not all members within a particular community will be equally vulnerable. Societal inequality influences both the extent of the health impact through the exposure and/or sensitivity pathway and the capacity of an individual or community to access adaptive options. An example of this differential at work occurred in New Orleans when the wealthy, informed, and mobile residents were better able to evacuate before Hurricane Katrina struck. People without such advantages were, through their lack of access to options, forced to remain and endure the consequences. Vulnerable subgroups are at increasing risk of having their vulnerability further exacerbated, as globally the gap between rich and poor is widening. Despite a surge in the size of the 'global middle class' between 1990 and 2005, the average country level income inequality increased around 20% (United Nations Secretary-General's High-level Panel on Global Sustainability 2012).

The relationship between exposure and incidence of harm is nonlinear. According to available global statistics, least developed countries (LDCs) represent 11% of the population exposed to natural hazards but account for 53% of casualties. This contrasts the situation for populations in the most developed countries, which represent 15% of human exposure to hazards but account only for 1.8% of all victims (Peduzzi et al. 2009). Complex factors therefore intervene in the translation of exposure risks and ultimate outcomes. The relationship between natural disasters and vulnerable populations has been described as a *double disadvantage*. The reason is that disasters present a feedback loop. First, they impact more heavily on disadvantaged populations, and the disproportionate damage incurred then further disadvantages these groups. Countries that are currently disadvantaged by retarded progress toward achieving MDGs commonly face additional burdens such as physical isolation; shortages in natural, human, and financial resources; and preexisting climate challenges. Collectively, these serve as barriers to countries reaching their MDGs. This situation exists in many Pacific Island countries.

Real concerns exist for escalation of vulnerability, as stalled international agreements for mitigation action have failed to make significant inroads in abating global greenhouse gas (GHG) emissions. This is despite the 100-year knowledge that emission of GHGs through the burning of fossil fuels increases atmospheric GHG concentrations and results in warming (Earth Observatory 2010). Current GHG levels will continue the process of warming for many centuries, even if emissions completely cease in 2012 (Gillett et al. 2011). Other human activities are exacerbating this trend.

A guardrail limit of 2 °C average global warming is the proposed international policy target, despite being acknowledged as 'not safe,' and would still accord future climate disasters and associated human misery. The 2009 Copenhagen Climate meetings agreed that there was "virtually no chance of limiting warming to 2 °C above preindustrial temperatures" (New et al. 2011). Extreme events are, by definition, rare. Heat extremes at three standard deviations (3σ) from the norm usually cover less than 1% of the globe in any given year. Over the past decade, these 'extreme extremes' have covered an unprecedented 10% of the globe, leading climate scientist, James Hansen (Goddard Institute for Space Studies) to predict that these extremes will become the new norm and that the 'new extreme' will be 5σ (Hansen et al. 2012).

A 66% probability now exists that such a high-emission nonmitigation future will yield warming outcomes in the range of 4.0–6.1 °C by 2100 (Rogelj et al. 2012). There are no projections as to whether such a world could support any semblance of life as we currently know it when weather extremes across the globe are increasingly falling outside the boundaries of customary extreme levels, with the relatively moderate average global warming reported by the IPCC in 2007 being 0.74 °C (IPCC, 2007c). Subsequent years since the publication of this report have been still hotter. Munich (2011) have been analyzing weather-related catastrophes for over 35 years and report that these catastrophes have almost tripled since 1980, flood loss events have gone up by a factor of more than three, and the number of windstorm natural catastrophes has more than doubled.

1.14.3 Pacific Island Exposure to Climate Change

Although a convincing body of evidence now exists demonstrating that the planet is warming, large uncertainties remain about the exact nature and timescales of future changes at the local level (IPCC 2012). Uncertainty about human responses to mitigation significantly contributes to this uncertainty. An indication of what can be expected from climate change, at the local scale, lies in the natural variation in existing weather patterns, as in addition to the warming trend, greater climate variability will amplify the extremes of current weather patterns (Durack et al. 2012). In 2011, the Australian Bureau of Meteorology (BoM) and the Commonwealth Scientific and Industrial Research Organisation (CSIRO) released downscaled projections for the Pacific Islands to assist the region to prepare for and adapt to increasing climate variability (Australian Bureau of Meteorology and CSIRO 2011c). Owing to the large geographical area, considerable variation exists in the modeled projections for future climate throughout the Pacific. Broadly, countries that experience extreme heat and droughts are likely to see more intense heat extremes and longer and more protracted droughts (Australian Bureau of Meteorology and CSIRO 2011c). Similarly, countries exposed to monsoonal weather patterns are likely to experience greater future rainfall variation, with some delays and weakening of monsoons and some intensifying of the monsoonal systems (Australian Bureau of Meteorology and CSIRO 2011b; IPCC 2007b).

PICTs are situated in cyclone- (typhoon-) prone areas and are subject to the vagaries of the ENSO, which bring quasi-cyclical rainfall variation. The waters in the western tropical Pacific are the world's warmest, and this and other unique features give rise to tropical cyclones (TCs) that can produce storm surges and flooding (Australian Bureau of Meteorology and CSIRO 2011a). Global monitoring of cyclones has been restricted to a short observational period and a changing observational capability through time. Owing to this insufficient data record, some researchers argue that it remains difficult to isolate significant trends in cyclone behavior (frequency, intensity, rainfall, etc.) over the background variation (Knutson et al. 2010). However, Elsner et al. (2008) analyzed satellite-derived lifetime-maximum wind speeds of TCs grouped by year over the period 1981–2006. They concluded that satellite measurements offer conclusive evidence showing significant increasing trends in maximum wind speeds of the strongest TC globally. This finding is qualitatively consistent with the heat-engine theory of cyclone intensity, that, as seas warm, the ocean has more energy that can be converted to TC wind.

Indeed, many PICTs are already experiencing early indications of new weather regimes. In October 2011, Tuvalu was forced to declare a state of emergency and sought urgent external assistance to facilitate water desalination. After a 6-month drought, drinking water supplies had run out and animals began dying after drinking the residual contaminated ground water. In the same month, exceptional monsoonal rains north of Bangkok generated the regions' worst flooding in decades. Shifts in the global frequencies and intensities of extreme heat waves, wildfires, droughts, and storm systems are already being observed across the globe. Coastal erosion and storm surge inundation are also becoming more common (IPCC 2012).

The January 2009 floods in Fiji were reported as the worst in the history of the country since the 1931 floods (Lal et al. 2009). Many parts of the country were affected by a number of consecutive flood events that spread over several days. The recent global assessment report on natural disasters of the United Nations shows that the number of natural disasters, the number of economic losses, and the number of people affected are increasing at a rapid rate and faster than risk reduction can be achieved (UNISDR 2009). Since the start of the new millennium, 2500 disasters have affected billions of people around the world. These crises destroy infrastructure, displace entire populations, and threaten ecosystems and people who rely on them to survive. Kofi Annan (Secretary General of the United Nations) reported in 1999 that 90% of the disaster victims worldwide live in developing countries, where poverty and population pressures force people to live in harm's way (Asian Development Bank 2011). He argued that the vulnerability of those living in risk-prone areas is perhaps the single most important cause of the observed inequitable distribution of disaster casualties and damage. Reducing the risk of disasters and conflicts, mitigating their impacts when they occur, and building resilient societies and economies are therefore at the top of the international agenda (UNEP 2010).

1.14.4 Pacific Island Sensitivity to Climate Change

The heightened sensitivity of the PICTs relates to particular characteristics, primarily their geomorphology, their relatively small size and isolation, and their level of economic development.

This region is characterized by volcanic archipelagos composed of low-lying islands and atolls where climate-related sea level rise could further amplify other stresses caused by natural phenomena (such as vertical ground movements due to tectonics and volcanism as well as the occurrence of extreme events such as storm surges) or human activities (Becker et al. 2012). Between 1993 and 2001, sea level rise over the western Pacific Ocean approached 30 mm year^{-1} (Church et al. 2006).

Sea level rise presents as the most certain and potentially devastating climate change impact for PICTs (Rodgers et al. 2009). Thermal expansion is contributing to rapid Pacific sea level rise, and this risk is especially pronounced for Funafuti Island (Tuvalu), where the 'total' rate of rise is found to be about three times larger than the global mean sea level rise over 1950–2009 (Becker et al. 2012).

Most of the 22 PICTs are classified as SIDS, as the combined land area covers only 553 959 km^2, with PNG accounting for 83% of this land area (FAO 2008). Dispersed over an area covering a substantial part of the earth's surface, PICTs are adopting the name the *Blue Continent*. A significant issue therefore for these scattered populations is 'the tyranny of distance,' which is exacerbated by having small populations, small economies, with the associated limitations in infrastructure and human resources, and high costs of connectivity. The combined effect significantly limits their options to initiate potent adaptive strategies.

Contributing to PICTs' climate sensitivity is their tropical climate, which brings a high prevalence of various infectious diseases – including food-borne and water-borne infections and several mosquito-borne infections (especially malaria in PNG, Solomon Islands, and Vanuatu and dengue in PICTs generally) (Cooper et al. 2002; Harley et al. 2011). Furthermore, as temperatures rise and climate variability increases, sensitivity to extremes of heat will also increase (including for outdoors workers) – especially among communities with high incidence of underlying cardiovascular and metabolic disorders (e.g., diabetes type II) (Hannaet al. 2012).

Existing climate among Pacific Islands offers significant challenges. These and other limitations, such as isolation and small land mass, contribute to the preexisting situation of slow progress toward achieving MDGs and development goals. The preexisting vulnerability of this region contributes to their sensitivity to shocks, regardless of the origin.

1.14.5 Pacific Island Potential Impacts of Climate Change

The potential impacts of natural disasters on PICTs cannot be overstated. These extreme events disrupt water and food supplies; damage infrastructure, buildings, and homes; destroy livelihoods; and bring an array of health problems. In the 1990s, for example, the cost of extreme events in the Pacific Island region was estimated to have exceeded US$1 billion. Losses caused by Cyclones Ofa and Val, which hit Samoa in 1990/91, totaled US$440 million, which was greater than the country's average annual gross domestic product (GDP) in recent years. In Niue, the damage bill from Cyclone Heta is estimated at about NZ$37.7 million, which is approximately 25% of Niue's GDP. Such proportional damage far exceeds the likely impacts for develop countries.

The full effect on population health of Heta has not been calculated, but it is likely to be significant, as health services were interrupted and livelihoods were hampered. The impact of this single event on the food security was profound. Cyclone Heta transitioned Niue from a food exporting country into one dependent on imports for the next 2 years (Food Secure Pacific Working Group 2008). Without good governance, extreme efforts of the local communities, and substantial external assistance, such destruction can reverse progress toward achieving MDGs by a decade (UNESCAP 2011). Such indications suggest that as climate change progresses, extreme weather events will drive the demand for increased effort to avoid further exacerbation of global health and development inequities and a widening of the gap between rich and poor nations.

Governments of PICTs recognize the potential impact of climate change. It poses a serious threat to most small island states and coastal populations. The 39th Pacific Island Forum Leaders in their Niue Declaration, warned "… urgent social, economic and security threats caused by the adverse impacts of climate change and sea level rise to our territorial integrity and continued existence as viable dynamic communities"(Pacific Islands Forum Secretariat 2008).

For many PICTs, sea level rise is arguably the most certain and potentially devastating climate change impact (Rodgers et al. 2009). Low elevation causes storm surge inundation of islands and salination of precious arable land and water supplies. A feature of many islands is having low-lying central areas excavated for production of taro. These low-lying areas are already subject to inundation, which will increase as the sea rises and threaten local food and water supplies (Woodroffe 2008). With limited available space, internal relocation of populations or agriculture is not an available strategy for many small island states. This reduces habitation adaptive options, amplifies sensitivity to natural disasters, and heightens vulnerability to the projected increasing intensity and frequency of these weather events (Hanna et al. 2012). Sea level rise could eventually make several countries, particularly atoll nations, such as Tuvalu, Kiribati, Tokelau, and the Keeling Islands, uninhabitable.

Higher islands are not immune to impacts from sea level rise. Higher islands anticipate losing significant proportions of their high-value land due to sea level rise, and Fiji and Samoa could also face serious challenges since most settlements and infrastructure cluster around the coastal zones. Their hilly inland regions may experience severe ecological changes because of mass relocation of migrants from the coast. Existing underlying health problems and limited local capacity to adapt also contribute to vulnerability.

Many Pacific Islands have a hot humid climate, and warming associated with increased climate variability would accentuate heat-exposure health risks. The potential impact of death from heat stoke is high when heat-sensitive humans, such as the very young, the aged, those with preexisting cardiac conditions, and those who need to continue working, are exposed to extreme heat events (Hanna et al. 2011). Humans begin to feel unwell when their core temperatures exceed 38 °C (~100 °F), and high humidity reduces the efficiency of physiological cooling mechanism of sweating.

Owing to the natural variability of climate, it has been difficult to attribute with certainty any specific extreme event, such as heat wave, to climate change. Authors examining single events continue to argue that specific heat waves could occur through natural climate variability alone (Dole et al. 2011). Indeed they could, and have done in the past. Chase et al. (2006) examined the 2003 European heat wave against data dating back to 1979 and analyzed the trends for extreme events – up to two standard deviations . Although concluding that the 2003 event exceeded three standard deviations (and was therefore *very extreme*), they argued that natural variability in the form of ENSO and volcanism was of much greater importance than any general warming trend in causing extreme regional temperature anomalies.

A widely adopted approach is to examine long-term trends that show a warming trend above the noise of natural variability (Nicholls 2009; UK Met Office Hadley Center 2008; Wu et al. 2012). Others examine the global pattern of record-breaking events. Globally, extreme heat events have been occurring with greater frequency, bringing temperatures and durations not previously experienced in recorded history (Hansen et al. 2012). Four of the world's leading climate research centers agree that the 10 hottest years on record have all occurred since 1998 (JMA – Tokyo climate Center 2011; NASA Goddard Institute for Space Studies 2010; NOAA National Climatic Data Center (U.S.) 2011; UK Met Office 2011).

In PICTs where temperatures and humidity are already high, which makes physical effort uncomfortable, the potential impact of further increases in temperature and humidity would create additional challenges for populations resident in these regions. Productivity can be threatened, and a healthy level of exercise is difficult to achieve against the risk of heat stress (Hanna 2010).

1.14.6 Pacific Island Adaptive Capacity

The pathway linking climate and human health is complex and multifactorial. Health effects arising from changes to local climate involving both extreme weather events and gradual shifts away from normal weather patterns are likely to be similarly complex. Contributing to the nature and intensity of associated health outcomes are the impacts exerted by changed weather patterns on local landscapes and ecosystem services, termed primary and secondary impacts (Butler 2010), and the degree of resilience or preparedness of the county's infrastructure to withstand these interruptions. All these factors influence a nation's capacity to offer population health protection and ultimately determine sequential health impacts.

The capacity of a country to withstand and cope with the added challenges of climate change is the ultimate determinant of vulnerability, and this is not a linear relationship. Relatively minor weather events can create major disruptions to health and development in developing countries that are already struggling to provide conditions for good health. In contrast, more major climatic events have been relatively well tolerated in countries with good underlying health status and highly specialized response and recovery systems. The differential can be seen by assessing the pre- and post-disaster living conditions. Wealthy countries can rebound quicker, whereas for poorer countries, depletion of internal resources commonly requires development aid and loans to rebuild major infrastructure and local livelihoods (Wisner et al. 2005). Recovery bills can channel the much needed resources from health-generating services, such as health and education. This impairment of earning and productive capacity of future generations is how disasters can generate a persisting influence, and notch by notch, lower community well-being. Repeated events eventually erode living standards.

Natural geophysical characteristics and high levels of economic and development contribute to adaptive capacity. Absence of these places limitations on a community's resilience to withstand challenges of the potential impacts of climate change.

The PICTs are classified as poor, falling in the low- and lower middle-income categories. The population of the region (10 million) has been predominantly rural, although urbanization is rapid and more than 50% of the population now resides in urban areas in a few countries (Pacific Institute of Public Policy 2011). Total population numbers are very small in several PICTs; for example, current estimates for Niue range from 1400 (Department of Foreign Affairs and Trade 2011) to 1000 (Pacific Institute of Public Policy 2011), and after peaking at 250 in the 1930s, the population in the Pitcairn Islands diminished to 63 people by 2009. In contrast, 6.7 million people live in PNG (World Health Organization Western Pacific Region 2011). Despite low total population numbers, some urban areas in the Pacific such as Tarawa in Kiribati and Majuro in Marshall Islands have extremely high population densities of up to 7000 people per square kilometer (Pacific Islands Forum Secretariat 2012). Significant Pacific Island populations now live abroad, primarily in Australia, New Zealand, and the United States. While this diaspora helps the local economy through remittances home, it undermines the skilled workforce capability and capacity in critical areas such as health (Russell 2011).

The adaptive capacity of PICTs to climate change is extremely limited because of their small populations and economies, isolation, limited human and ecological resources, and dependence on international trade and in some cases foreign aid (Secretariat of the United Nations Framework Convention on Climate Change 2007).

1.14.7 Pacific Island Vulnerability to Climate Change

It can be seen then that the ultimate level of vulnerability is derived from a combination of these determinants. The main factors accounting for risk are intensity of the hazard (exposure), sensitivity of the local environment, culture, and population, which together generate potential impact, and the levels of poverty and governance determine the adaptive capacity. The increasing intensity of TCs is associated with increasing mortality, direct human exposure, and the number of coastal population living in low-lying areas being especially vulnerable to the high winds in category V and above. The protective power of adaptive capacity ought not be underestimated. A trend analysis of mortality risk based on the observed TC database conducted by Peduzzi et al. (2012) demonstrated that vulnerability parameters carry more weight in less-intense TC and, conversely, that the role of population exposure in mortality risk grows with the intensity of the TC. Their analysis revealed that poverty levels (low GDP per capita) accounted for 91% of the mortality loss for category I TC, yet this decreased to 31.1% for category V. At lower cyclone intensities therefore, only the poorest suffer heavy losses, whereas in very intense TC, the impact is more evenly felt, at least in the immediate term. Coastal population living in low-lying areas (less than 10 km from the coast) was also found to explain a large share of losses from high-category TC, whereas remoteness increased the vulnerability. According to the Peduzzi analysis, TCs seem to be more dangerous in rural/remote areas than in cities, which they postulate could be attributed to several factors, such as improved early warning, better infrastructure, and quicker access to external rescue and aid from humanitarian services in urban areas.

Basic health infrastructure is lacking for many communities in the PICTs, especially among remote islands, with significant ramifications for population health. For example, 60% of Papua New Guineans do not have sustainable access to improved water source, and in six PICTs, 50% or more of the population live in houses without sanitation. Only 25% of the people in the FSM have domestic sanitation, and in the Solomon Islands, the figure is 32% (World Health Organization Western Pacific Region 2011). The underlying health problems coupled with their limited local capacity to adapt have intensified the PICTs' vulnerability to a range of potential threats (Hanna et al. 2012). These countries currently face extreme challenges in providing basic health needs for their citizens, and this seriously compromises their capacity to finance additional climate change adaptation strategies. Mounting an effective response to adapt to climate change will therefore require assistance from donor countries, and PICTs welcome this.

Although the need for adaptation to climate change has been recognized via regional and international initiatives, practical adaptation measures remain small in number (Barnett and Campbell 2010). In 2001, Barnett argued that uncertainties with regard to anticipated climate change impacts on PICTs were hindering policy making (Barnett 2001). A decade later, despite increasing evidence and (incipient) awareness of risks to human health and the quickening pace of climate change, global policy action continues to fall well short of what is required to protect the most vulnerable. Few regionally contextualized studies or detailed analyses have been conducted in the Pacific region to confirm what real health risks of climate change exist for these communities. Addressing this lack of information is critical to the development of well-targeted adaptation strategies by PICTs (Hanna et al. 2012).

Effective adaptation strategies are expected to produce better outcomes with respect to both the biogeophysical conditions (the living environment) and the socioeconomic well-being of PICTs' populations. These constitute 'no-regrets' policies (Intergovernmental Panel on Climate Change 2007), as notwithstanding climate change, strong arguments exist to justify such investments, for example, weather-proofing water and sanitation supplies. Climate adaptation investments that increase underlying population health also boost resilience to cope with future climate and other risks.

1.14.8 Case Study: Food Security – Linking the Food, Nutrition, Health, and Climate Nexus in Vulnerable Countries – The Pacific Islands

To summarize, the previous sections mapped the determinants of vulnerability of the Pacific Islands to their climate and future extremes. Climate change is associated with shifts in climate patterns. This shift is composed of a background level of global warming and a trend toward alterations in precipitation events and climatic extremes. These extremes can be periods of intense heat, protracted droughts, or intense storms (TCs/typhoons), which are associated with strong winds, extreme rainfall (hail or snow), and high sea surges. Intense cold spells will also occur in certain regions, as experienced by Europe in early 2012. The severity of the weather that occurs at a particular location and the degree of shift in climate patterns determines the intensity of exposure. Vulnerability therefore is the combination of the climate impacts and the capacity of the community to protect itself and recover from the damage or interruption to services arising.

The following sections of this chapter explore the ramifications of human health arising from climate-related interruptions of food supplies and how this can carry ripple effects through subsequent generations.

1.14.8.1 Food and Climate

Communities develop their lifestyles, agriculture, and cultural practices in response to their natural environment. Dietary staples provide an example of environmental influences on cultural behaviors. People living in high-rainfall areas tend toward diets based on rice, whereas populations from drier regions consume wheat or durum. Although these cultural practices may be enduring, they are not static over generations. Ecosystems exist in a constant state of flux, responding to natural and human-induced interventions. Local inhabitants finely attune their practices in response to these changes and to accommodate their usual range of climate variables, including the extreme fluctuations that occur infrequently.

Long-term shifts in regional weather, hydrology, and soil structure bring relative benefits or disadvantages to certain species of plants and animals, and these pressures of relative advantage underpin the process of evolution. Under normal circumstances, this is a slow and barely discernible process. The rapid pace of climate change will create ecosystem disruptions that are too 'sudden' for smooth ecosystem adaptation. Species need many generations to fully adapt to changes. Those with slow reproductive rates and small numbers of offspring need hundreds of thousands of years. Those unable to thrive in the new environment will decline in numbers. Estimates suggest that even if global temperatures increase by only 2 °C, biodiversity will be significantly diminished and up to 20–30% of species could face extinction.

Humans have managed to inhabit most of the earth's landmass under vastly diverse environments. This success is directly attributable to humans' ingenuity, adaptability, and capacity to optimize conditions and manipulate the environment to suit their survival needs. Long-term survival success of a population is determined by their capacity to provide for their life-sustaining needs, that is, to develop effective resource utilization and management. Throughout human history, the most successful societies have expanded this practice to develop empires, achieved through the accrual of advanced technologies. This advantage facilitated travel and the capacity to exert influence and reap resources from other areas, usually from less technologically advanced societies. Over time, this additional wealth allowed for the further development of complex cites and self-sustaining urban environments, with food and water resources pouring in from outside, through a system of organized trade.

Societies without advanced technological development have been forced to sustain themselves on their own local resources and trading spare resources for the additional goods and services needed. Power imbalances determine the terms of trade, and smaller, weaker societies tend not to be in a position to force favorable terms. In the modern era, international aid programs have evolved to help address some of these inequities, but these relationships remain tenuous because of the underlying power imbalances. SIDS have not enjoyed the opportunities for power and wealth accumulation as *empire states*; indeed, smaller nations have often lost considerable wealth to powerful nations.

Disruptions in customary rainfall patterns will have a powerful effect on reliability of food production.

Despite the trappings of wealth enjoyed in developed nations, the *fundamental* necessities of life are not – as is increasingly assumed – access to cars, computers, or plasma television screens, but rather food, water, air, and shelter. Civil society and peace are also regarded as necessary, to assure longevity in harmony and a rights-based method of sharing resources, ideally in a fair and equitable manner (UNICEF & Innocenti Research Centre 2008; WHO Regional Office for Europe 1986). Climate change threatens to interrupt the supply of all these basic necessities, and hence threatens human survival. As outlined in Chapter 2.5 Role of Engineering Plants for Abiotic Stresses (Biodiversity Loss and Ecosystem Function), food and water are ecosystem services and their provision depends on the regional natural environment, as determined by climate (the range and variability in temperature, wind, sunshine, rainfall, and humidity), water availability, terrain, and soil quality. Article 1 of the United Nations Framework Convention on Climate Change (UNFCC) defines adverse effects of climate change as the link between ecosystems and human health and well-being.

> 'Adverse effects of climate change' means changes in the physical environment or biota resulting from climate change which have significant deleterious effects on the composition, resilience or productivity of natural and managed ecosystems or on the operation of socio-economic systems or on human health and welfare
>
> Article 1 UNFCCC (UNFCCC 1992)

The optimal food-growing conditions consist of a balance of sunshine in a moderate temperature range and regular rainfall, yet with an absence of damaging storms. Societies with access to large tracts of fertile land in these ideal climatic conditions and an equitable system of distribution of agricultural goods are most fortunate. Access to regular water supplies is dependent on regular rainfall, on a landform that allows for collection and delivery, such as valleys for damming and rivers for transport. Delivery to the point of use requires technology and sufficient wealth to construct the necessary infrastructure, canals and irrigation systems to augment rainfall in agricultural regions, and wells or a system of pipes and purification plants to supply domestic needs. Without this infrastructure, people must live close enough to a river or well and have the means to transport personal requirements. In the absence of purification, the risk of contamination and disease is high.

In general, the more removed from ideal agricultural conditions, or technology to overcome environmental shortfalls, the more tenuous is the access to regular supplies of the basic necessities of food and water and the greater is the dependence on alternative methodologies, such as accessing external supplies via trade. Populations living in marginal environments, and without financial wealth and capacity to override their shortfalls, are extremely vulnerable to climate change, considerably more than wealthy countries in ideal agricultural environments.

The lack of infrastructure clearly has not precluded human settlements growing food, and this again testifies to human ingenuity and adaptive capacity. However, human history testifies that both long- and medium-term climate changes have often destabilized civilizations (McMichael 2012), delivered primarily via food shortages, consequent hunger, disease, and sociopolitical unrest. The drought-famine-starvation nexus has been the main, recurring, and serious threat to health and has precipitated large-scale migrations (Fust et al. 2009).

Trade allows for international food redistribution, and this becomes critical when climate conditions create shortfalls. In 2008, 2010, and 2011, climate disruptions occurred in many regions: a heat wave in Russia; droughts in the Horn of Africa, Russia, China, and Brazil; and flooding in Pakistan and Australia. Global food yield reductions escalated prices (Oxfam Australia 2011). Vulnerability to these effects falls acutely on the poor because of their limited capacity to absorb price rises (Fust et al. 2009).

Climate science is predicting the end of the climate stability characteristic of the Holocene period, which provided ideal conditions allowing agriculture to evolve and flourish. Disturbing this albeit dynamic balance will bring interruptions to food supplies and a range of negative consequences for human health and welfare. Above a global temperature increase of 1.5 °C, agriculture in all regions will be vulnerable to climate change. Global food production potential is threatened at +1 °C local temperature change and can accommodate no more than +3 °C before beginning to decline in all regions (IPCC 2007b). Humans cannot divorce themselves from the ecosystems that support them. Food and water supplies lie at the core of this dependence. Societies that face the greatest and most immediate threats to climate change are those that are currently unable to be self-supporting in their food needs, whose food and water supplies are already precarious, or whose food and water harvesting regions are at particular risk from climate change and longer term change, such as through sea level incursion. In this context, Pacific Island nations are especially vulnerable to the effects of climate change, disasters, and the slow insidious impacts.

1.14.8.2 Linking Vulnerability to Health

The impacts for communities are unlikely to be felt as singular linear pathways in the way that researchers tend to examine cause and effect, but rather as compounding layers that overlay, interact, and exacerbate the pressures. It is possible for some of climate–health interactions to have negating or ameliorating effects; however, climate change impacts are likely to be primarily negative and cumulative (McMichael and Woodruff 2002). In some instances, these may result in multiplicative effects on societies and bring catastrophic outcomes.

We have discussed that air, water, food, and shelter are the minimum requirements for health, well-being, and, indeed, survival. It has been understood since the times of Hippocrates (and possibly beforehand) that when access to all these is insufficient, or sources are contaminated, then ill-health ensues. Health, manifested as health status, is therefore an *outcome* of a person's access to these fundamental health determinants. Yet their provision lies outside the formal health sector and so are commonly regarded as 'externalities' to health. The role of the formal health sector, particularly hospitals and doctors, is seen as not delivering these basic health prerequisites, but rather, as striving to reverse the disease or ill-health precipitated by deficits in these external factors.

Climate science is projecting that changing climate trends will affect air quality, water quality and quantity, and shelter (IPCC 2007a). Food security will also be impacted. Food is central to good health, and yet despite this criticality, and decades of advances in food production and distribution systems, universal access to sufficient amounts of nutritious food is still not achieved. In 2009, there were over 1.2 billion people who were undernourished. The 2010 data suggest that 925 million people are undernourished, which represents 13.6%, or 1 in 7 of the estimated world population of 6.8 billion (World Hunger Education Service 2012). Nearly the entire undernourished are in developing countries.

A reliable food supply is required for populations to flourish and grow, and agricultural yield is climate dependent. Approximately 11 000 years ago, in many parts of the world, villages and towns almost simultaneously emerged alongside developments in agriculture. This could only occur when advances in farming methods reached a stage that enabled food production surplus to one's domestic needs. This timing also coincides with a period of relative stability in the climate, where the average global temperature had warmed to and then largely remained within a 0.6 °C range of 14.6 °C (IPCC 2007c). This temperature and stability were not only unusual but also proved ideally suited for agriculture and allowed for the production of reliable yields and the evolution of villages and towns.

Since that time, increasingly urbanized and technical societies have shifted away from subsistence or self-catering lifestyle toward complex food systems, where access to sufficient nutritious food supplies becomes less dependent on personal endeavor and more dependent on an array of sociopolitical and economic factors, which can be distorted and manipulated. In keeping with this trend, more recent shifts from domestic farm ownership and sales via local markets to national or corporate enterprises and food distribution giants, access to food becomes politicized and is intertwined with trade and national powers (Dixon et al 2009).

The small size, both in terms of global economic influence and local geography, therefore limits the adaptive capacity of states such as the PICTs. Coupled with their high exposure, sensitivity, and high potential impacts, this makes PICTs extremely vulnerable. The following case study demonstrates this vulnerability, its complex nature, and how factors reinforce each other to exacerbate the risk of poor health outcomes.

1.14.8.3 Food Insecurity: A Climate Change Risk

Food security therefore serves well as a case study to depict climate pressures ultimately affecting health outcomes and the interlinking of environmental forces, vulnerability, and complex socioeconomic and political filters. This case study outlines the complex systems network underpinning the environment, the food–health nexus, and the long-term ramifications of these influences. Starting from an examination of vulnerability, inability to withstand shocks (be they climate or economic in origin), and food insecurity as food and fuel prices increase and yields fall, we explore the impacts on vulnerable subgroups, at the domestic level, the effects on nutrition and health (maternal and child), and the ultimate capacity to contribute to society and its economic status. This sets up a feedback loop as a poverty trap.

Vulnerability to both climate change and food insecurity is strongly linked with poverty. The poverty and vulnerability experienced by PICTs reflect the stresses placed by a wide range of factors on these societies. According to the AusAID the factors are as follows:

- Weak economies – vulnerable to economic shocks and not providing sufficient jobs.
- Increasing urbanization – loosening the ties within extended families and leading to the creation of squatter settlements with greater dependency on rural areas.
- High susceptibility to natural disasters – stretches the resilience of families, communities, and states.
- Interethnic conflicts – weakening social cohesion and the state (Kidd et al. 2010).

The Commonwealth Vulnerability Index (Atkins et al. 2000) combines vulnerability to both economic and natural shocks and ranks Vanuatu, Tonga, Kiribati, and Samoa among the five most vulnerable states worldwide. In addition to climate change, PICTs are also vulnerable to natural disasters; for example, those situated on or near active fault lines are susceptible to earthquakes and devastating tsunamis, which take a heavy toll on development progress. The tropical climate in many PICTs makes them also vulnerable to landslides, especially in areas that have been logged, and epidemics.

1.14.8.4 Food Insecurity through Economic Vulnerability

Vulnerabilities associated with macroeconomic shocks and natural disasters are neither evenly distributed across the globe nor evenly distributed within countries. Their impacts fall disproportionately on the poor on whom the effects may be cumulative and irreversible, and the inequality (measured as the Gini coefficient) is worsening (Urbano et al. 2010). Developing countries, especially small countries with limited resources, have little reserves to rechannel resources for rebuilding. Owing to their limited power in trade negotiations, they are at the mercy of powerful trading partners, which can force compromises to their nation's best interest. Indeed, they are heavily dependent on these partners for aid and must contend with the uncertainty that aid may not always be (1) available, (2) timely, or (3) appropriate to needs. In the situation of increasing climate disasters and continuing global financial crises, an increasingly likely scenario is one in which foreign governments may be pressured by their home constituents to focus on internal reparation and rebuilding at the expense of international aid generosity or meeting their aid obligations.

In 2012, the PICT's demand for food is being increasingly serviced by imports. Basic staples such as rice and wheat for flour have become key substitutes for traditional diets and are now central to the Pacific Islander's daily diet (FAO 2008). Deteriorating terms of trade, rising external debts, and inflation stifle the capacity of Pacific Islanders to adequately meet their nutritional requirements from imported food alone. Ramifications of both the current global economic crisis and the 2008 global food crisis have therefore been felt keenly by the PICTs, through declining tourism income and falling amounts of remittances (and falling values of those denominated in US dollars) and depreciating values of internationally held trust fund portfolios (Kidd et al. 2010). Their economies are weakening, and living standards are falling.

Vulnerability assessments carried out in 2009 and late 2010 indicate that the more remote and import-dependent Pacific Island economies of Kiribati, FSM, Republic of the Marshall Islands (RMI), Tuvalu, and Tonga are particularly exposed to the economic burdens of higher global fuel and food prices. Fiji, Solomon Islands, and Vanuatu are also vulnerable because of high inflation and structural issues and their geographically dispersed population (UNICEF 2011a). The particular vulnerability of Tonga and Vanuatu lies in their high frequency of natural disasters, and the resultant effects on agricultural production, and very limited social protection activities. Conversely, the economies of the Cook Islands, Niue, and Samoa are among those of the better performing Pacific nations, with consistent economic growth, impressive social development, and good progress toward achieving their MDGs, especially MDG 1 on eradicating extreme poverty and hunger (UNICEF 2007), yet there is great disparity in income growth both between and within countries.

Since the rapid escalation in food prices during the 2008 global food crisis, prices fell only briefly. The Food and Agriculture Organization (FAO) generates a global Food Price Index (FPI) to enable interannual comparisons. In June 2011, the FPI was 39% higher than in June 2010, and only marginally less than its all-time high of 238 points in February 2011, and cereal prices were 71% higher than in June 2010 (FAO 2011). The steady rise in food prices in the Pacific has caused widespread concern, for example, in Kiribati (with a GDP per capita of US$1142 in 2009), prices for staples such as rice increased from AUD$16 per 20 kg bag in 2006 to AUD$21 in 2008 (UNICEF 2011a). Vanuatu populations have been exposed to price increases ranging from 40% to over 100% for staples such as taro, banana, and yams (UNICEF 2011c). According to the regional sentinel monitoring system, a majority of vulnerable families surveyed in six Pacific Island countries reported increased economic stress in meeting food expenditure because of rising food prices, as the cost of some staple food items were up by as much as 50–100% since 2009 (Miskelly et al. 2011). Households are forced to spend 39–50% of their budgets on food (Food Secure Pacific Working Group 2010).

Compounding the food stress imposed by import price rises is decreasing local food yields. Some agricultural crops in Vanuatu are already showing signs of stress under current climatic conditions. The food price increase takes the greatest toll on the poorest households because of their higher relative expenditure on food. Food stress is highest among the urban poor, whereas rural poor have a higher likelihood of supplementing their food supplies by resorting to subsistence farming (Miskelly et al. 2011). Food poverty indicates the inability of households to feed themselves. Household surveys that have calculated the proportion of people falling below food poverty lines is high: 16.6% of the population in Palau, 11% in FSM, 10.6% in the Solomon Islands, 7.4% in Vanuatu, and 4.9% in Kiribati (Kidd et al. 2010).

There are significant differences across countries, with import dependency ranging from 36% in Kiribati to over 80% in Palau (Parks and Abbott 2009). These figures represent import dependency at the national level; however, significant variation also exists within countries, especially between urban centers and rural areas. The share of total expenditure on food and transport in urban area ranges from 35 to 40%, whereas the range is less in rural areas, from 20 to 25% (Global Study on Child Poverty and Disparity 2009). Urban dwellers who rely mainly on purchased foodstuffs are disproportionately more affected than rural households who live outside the cash economy (McGregor et al. 2009) and are therefore more at risk of undernutrition and consequent ill-health. Having no significant food exports, the inhabitants of Polynesia and the atoll microstates are similarly vulnerable because of their dependence on imported food.

Within the vulnerable urban groups, those most likely to experience the greatest degrees of hardship and poverty will be (1) the very young, (2) the very old, (3) people living with disabilities, (4) those who have no source of regular income, or (5) those with no access to adequate land on which to grow food for consumption and/or sale (Parks and Abbott 2009). Households headed by women and the elderly will be very vulnerable. It follows then that children living in female-headed households are likely to be especially disadvantaged.

Owing to the strong emphasis on caring and redistribution that exists within the extended family system, poverty in the Pacific Island context does not necessarily mean outright hunger or destitution. However, the poor face a continuous struggle to meet essential daily/weekly living expenses, particularly those that require cash payments. Furthermore, the subsistence sector, which in the past has played an important role in sustaining livelihoods in the Pacific Island economies through difficult times, is having a diminishing role. The trend toward urbanization is eroding the traditional support networks that for generations have helped safeguard food security in times of hardship (Hanna et al. 2012).

High food prices accentuate the vulnerability of the rural and urban poor. Eroded purchasing power inevitably leads to difficult decisions and a deterioration in the amount and quality of food consumed. A sentinel monitoring system conducted in 2010 (UNICEF 2011a) revealed that a majority of vulnerable families, particularly those in urban areas, were experiencing increased economic stress in meeting food expenditure because of rising food prices and the global economic crisis. Food stress was reported by 63% families in Solomon Islands, 77% in Tuvalu, and 54% in Kiribati (UNICEF 2011a), and this stress forced changes to the type and quantity of food consumed as well as to the cooking methods.

Most PICTs have an extraordinary dependence on fish for food security because of limited access to other sources of animal protein, particularly in rural areas (Bell et al. 2011a,b). The world's oceans and fish stock have become increasingly under threat from ocean acidification, rising seawater temperatures, ocean deoxygenation, sea level rise, pollution, and the overuse of marine resources (overfishing) (Noone et al. 2012). The average acidity of the upper ocean has already declined by around 0.1 pH unit, which represents a 30% increase in acidity since the industrial revolution. Three of these interacting factors, warming, acidification, and hypoxia, will cause substantial changes in marine physics, chemistry, and biology (Plymouth Marine Laboratory 2012). Many PICTs are heavily dependent on their fisheries resources for economic development, government revenue, food security, and livelihoods and are vulnerable to any change in the status of these resources (Bell et al. 2011a,b).

Through rising food prices, fresh or frozen meat and fish, now considered a luxury, have been predominantly replaced by cheaper alternatives such as tinned fish, noodles, and turkey tails, and where able, vulnerable families are relying on backyard gardens and are consuming much less fresh protein (Miskelly et al. 2011). Among the poor, rice, flour, and milk were reportedly considered expensive, as women sought cheaper substitutes or cooked with them only rarely.

Households commonly used food rationing to keep food costs down, and the poorest families reported living on tea and starchy basics. The report revealed that because of their lower cultural status, children and women often are not prioritized at the meal table and may only consume one or two meals a day. Another practice commonly reported was for children to go without breakfast and eating meager or no lunch at school (UNICEF 2011a).

As diets become more and more restricted, they become increasingly deficient in micronutrients, with potentially pernicious long-term consequences for growing children and pregnant women. Malnutrition, including micronutrient deficiencies, is already common across the Pacific, and the changes in household food consumption patterns brought about by the economic crisis is likely to have increased these problems (Parks and Abbott 2009). Despite a proportion of the population still relying on traditional subsistence agriculture, the food insecurities faced by many Pacific Island countries and households will further exacerbate if impacts of the economic crisis and high food prices do not abate. The World Bank predicts an increase in poverty as families face a triple squeeze from falling incomes and remittances, rising costs, and shrinking public expenditure, including aid (Rawe et al. 2012).

1.14.8.5 Child Health

There is considerable evidence demonstrating that food shortages in childhood can have important and sometimes permanent cognitive, motor, socioemotional, educational, and economic repercussions across the life course (Parks and Abbott 2009). Food-insecure children have twice the odds of having only 'fair or poor' health, and their odds of being hospitalized are almost one-third larger than food-secure children; the greater the severity of food insecurity, the greater is the health risk (Cook et al. 2004). A strong link has also been established between poor maternal nutritional status and low birth weight and increased infant and childhood morbidity and mortality (Amuna and Zotor 2008). Poor mothers are more likely to die in childbirth (Inter-Agency and Expert Group on MDG Indicators 2008); the nutritional state of the mother and fetus is therefore critical, as the impacts of undernutrition linger for the life of the child and the diminishment in their health and earning capacity flows on to subsequent generations.

Prenatal environment triggers developmental changes in the endocrine, organ, and physiological characteristics of the fetus that may persist after birth. The list of postnatal traits shown to be influenced by the prenatal environment has expanded to include such important functions as immunity, reproductive function, growth rates, and muscle mass (Prentice and Goldberg 2000). Furthermore, the undernourished pregnant women experience metabolic suppression of immune system synthesis, which contributes markedly to the high rates of perinatal and infant mortality seen in many poor countries (Amuna and Zotor 2008). An undernourished mother suffering nutritional stress has intrauterine growth restriction, as a physiological coping mechanism to preserve her own health, and delivers a low-birth-weight baby. The early and later life consequences for her child include type 2 diabetes mellitus, hypertension, and hyperlipidemias (Lucas et al. 1999), all of which are prevalent and rising rapidly in the many Pacific communities (SPC 2010). Children who are compromised at birth have a higher susceptibility to diseases such as diarrheal diseases, malaria, etc.

The percentage of Pacific Island children born with a low birth weight (<2500 g) varies from 3% in the Cook Islands to 18% in FSM. Another key indicator for childhood undernutrition is the proportion of children classified as underweight when under 5 years. In the Pacific, the figures range between 1.6% in Tuvalu and 16% in Vanuatu, and in Vanuatu, 20% of children under 5 years are stunted (Parks and Abbott 2009). Globally, it is estimated that stunting, severe wasting, and intrauterine growth restriction together are responsible for 2×2 million deaths and 21% of disability-adjusted life years (DALYs) for children younger than 5 years (Black et al. 2010). Stunted children may never regain the height lost as a result of stunting, and most children will never gain the corresponding body weight. It also leads to premature death later in life because vital organs never fully develop during childhood (Finnigan and Luetz 2009). Results indicate that children living in households belonging to the lowest wealth index quintiles are more likely to be underweight and children from households within the richest quintile are more likely to be overweight, which carries another set of health risks. Stunting remains throughout life. Stunted women have a 95% higher need for assisted deliveries when they reach childbirth, and if operative delivery services are not available, the lives of the mother and child are at risk (Black et al. 2008). Many remote islands have limited obstetric services, and many poor are unable to afford travel to major centers for health care.

Deficiencies in micronutrients, such as calcium, iodine, the B vitamins (especially folic acid and vitamin B_{12}), and vitamin D, result in health problems for maternal and child health (Black et al. 2008). Zinc deficiency in children results in increased risk of diarrhea, pneumonia, and malaria, whereas deficiencies in iodine result in goiters, congenital hypothyroidism, and developmental disability (Black et al. 2008). Vitamin A deficiency reduces immune system functioning, which places the child at a greater risk of succumbing to infectious diseases (Rawe K et al. 2012). Iron deficiency anemia is another significant public health concern for the Pacific region. Figures are not available for all countries; however, where data exist, 6 of 10 children are anemic, and for Vanuatu, 34% of children aged 6–59 months are anemic (Parks and Abbott 2009).

Many other health problems among Pacific Island children result from undernutrition. Every year, around 18 000 children under 5 years of age die (13 000 in PNG, 2500 in Timor-Leste); four of five of these children are under 5 years of age (Parks and Abbott 2009). Maternal mortality is also high, which leaves her other children without a mother, which further jeopardizes their health. Social services, such as disability services, are underresourced, especially across the outer islands and remote areas. It is estimated that up to two-thirds of childhood disabilities are preventable, thus there is a lot of scope for improvements in prevention of disability, particularly in safe motherhood and deliveries, nutrition, water, and sanitation (Tavola and Whippy 2010).

Diarrheal diseases are already the most common cause of illness and the second highest cause of death of children under

5 years of age, causing as many as 1.6 million deaths (17%) per year (WHO 2009). It is estimated that 80% of the mortality from diarrhea is attributable to unsafe water and lack of sanitation (with nearly 90% of the global burden of diarrheal disease caused by the lack of access to safe water and sanitation) (Parks and Abbott 2009).

1.14.8.6 Climate and Food and Health

The relationship between rainfall and diarrhea is well established, both in terms of incidence (higher number of cases related to reduced water availability) and the mortality rates of children under 5 years (WHO 2011). Climate change is projected to bring greater variability in rainfall patterns (Australian Bureau of Meteorology and CSIRO 2011b). Both excessive rainfall and rainfall shortage can be problematic for human health. Heavy rainfall contaminates drinking water supplies, whereas water shortages lead to water conservation, reuse, and sharing, which risks multiple mechanisms for contamination. Lack of access to clean water exacerbates the burden of diarrheal disease and increases the risk of death and disability, especially in children who need more water per body mass compared to adults.

Water security, defined as regular access to adequate quantities of clean water, requires water availability (rainfall) and expensive infrastructure to purify and deliver to the end users. Developing countries face many challenges in delivering water security to their entire population. Children are especially vulnerable to infections that cause diarrhea (Parashar et al. 2003) not only because their immune system is less robust in fighting infections than that of older people but also because their behavior (playing on the ground and hand to mouth behavior) increases the likelihood of exposure to infectious agents from water and other people, especially family members and other children. Nutrient absorption from the diet is interrupted during bouts of diarrhea, hence diarrheal diseases further compromise the nutritional status of the child and increase susceptibility to other opportunistic parasitic infections. Malnutrition becomes a double burden, as the reduced resistance to disease exacerbates the condition (WHO 2009). Climate change will directly affect the risk to children from diarrheal disease if the provision of adequate and safe food, water, and sanitation are compromised through changing rainfall patterns.

The mortality and morbidity risks from environmental conditions are 44% higher in children under 14 years than in the rest of the population (United Nations Secretary-General's High-level Panel on Global Sustainability 2012). By virtue of their early stage in development, children and especially very young children are at greatest risk of injury, disability, and death from the consequences of the changing climate system (Hanna 2011). With their dependence on others for sustenance, nurturing, protection from infection, and physical harm, the susceptibility of children to threats is increasing (WHO 2009). Overwhelming scientific evidence suggests that the three greatest killers of children – malnutrition, diarrheal disease, and malaria – will be exacerbated by climate change (Schneider et al. 2007). The risk of harm is greatest for children living in developing countries, because of the dual disadvantage, that is, extreme climate effects and because poverty limits their ability to respond.

Socioeconomic situation can place further barriers to a poor child's prospects. In situations of national poverty, funding cuts to schools lead to declines in education quality and the higher costs are transferred to parents. In extreme domestic poverty, one of the difficult decisions can be to withdraw children from school because of inability to afford the direct schooling costs or requirement of children to supplement their family income. Often, girls' education will be sacrificed, and if in later years she becomes a sole mother, her children are destined to remain in the poverty trap. Malnourished students perform poorly at school, and this also predisposes the child to a future with restricted economic opportunities. A poorly nourished generation deprives a nation of its most valuable resource, human contribution to society, and the economy. Speaking on these effects of climate change in Kiribati, His Excellency Mr. Anote Tong, President of the Republic of Kiribati, claimed " Climate change is eating away [adolescents'] future and putting their physical and mental development at risk" (UNICEF 2011b).

Climate change will deliver many challenges. Some are already beginning to emerge, climate science suggests more, and much more is to follow. Countries, particularly vulnerable countries, need their populations to rise to the challenge, and to do this, they need to optimize the health of every child.

1.14.9 Summary

The vulnerability of Pacific Island countries to climate change is driven by a number of determinants (Pachauri et al. 2007; UNFCCC 2007). Essentially, the two key determinants, (1) projected *levels of exposure* to intense forces of climate change and (2) *sensitivity to those exposures*, are both high. Their sensitivity arises not only from a range of geophysical attributes but also, for many islands, from their preexisting vulnerability to shocks of any nature due to challenges of resource limitations, which hampers their capacity to initiate large-scale and complex responses. This combination puts PICTs into the highly vulnerable category.

Health impacts arising from a changing climate will not be distributed evenly around the globe (Adger et al. 2006). In the short term, there will be some winners and many losers, based on the variable exposures and vulnerabilities across the globe.

When conducting a vulnerability analysis for a specific location, it is important to understand existing vulnerabilities, threats, challenges, coping capacities, and potential strengths. Step two involves an assessment of the society's capacity to prepare for, withstand, and minimize harm and then recover from those effects when they do occur. The third step involves identifying the trigger points, beyond which significant harm will emerge and potentially overwhelm response capacity. Examination of the likelihood or timing of encountering such scenarios is the next step, which serves to prioritize strategic planning.

A worst-case scenario is one in which (1) climate forces will be strong and (2) community resilience is relatively weak. Coexistence of these pressures at any level is extremely risky and renders the populations especially vulnerable, and the resultant impact will be proportional to the capacity of the community to withstand and rebound from the climate challenges confronting them. Where the combination of these pressures is particularly intense, a high likelihood exists that the associated outcome will be catastrophic and potentially lethal to community well-being and ultimate survival.

To summarize, the case of food security in small Pacific Island countries clearly demonstrates how climate change affects highly vulnerable developing countries. The health of the populations is further compromised through the mechanism of intensifying food (and water) insecurity, which renders them even more vulnerable and less able to escape the poverty trap. We have seen how Pacific Island countries are vulnerable to natural disasters that can cause temporary food insecurity. In the past, traditional smallholder farming systems have proved to be robust, productive, and protective in the face of adversity. These systems need to be supported and strengthened to assist Pacific Island countries to meet the challenges of increased food prices. Food and water security are health issues and must be protected to secure human health.

Nutrition is one of the most significant factors determining risks to the health of women and children. Its importance extends beyond ensuring survival of an individual. Nutrition provides the source from which future social and economic opportunities flow for generations to come. Investing in children and women is necessary to protect population health now and into the future. Single approaches are unlikely to succeed when people live in a multithreat environment. Protection against climate change should be part of a suite of actions that optimize public health, which includes the expansion and the subsequent ongoing maintenance of essential health and social services for children and women (health, education, HIV prevention, and protection from abuse, violence, and exploitation). This needs to occur against a background where economic challenges are likely to persist and be exacerbated by climate change. Per capita health expenditure may eventually diminish, as competing budgetary demands to fund recovery from natural disasters and rebuild infrastructure consume an increasing proportion of total government expenditures. Countries letting health slide are counterproductive, and maladaptive, as underinvestment in fundamental public health compromises nation's future security and prosperity; these are dependent on a healthy population.

1.14.10 Adaptive Strategies

Basic strategies to enhance population health include

- supporting national agriculture;
- implementing universal improved water supplies and domestic sanitation – for urban and rural dwellers;
- provision of universal maternal and child health programs;
- provision of micronutrient supplements for children (vitamin A and zinc);
- micronutrient fortification (iron and salt iodization);
- expanded immunization coverage for children;
- deworming and other nutrition programs at school;
- introducing schooling fee structures that allow for education of all children;
- increasing and improving girls' schooling;
- implementing community-based nutrition promotion;
- providing support for women's reproductive role (and family planning);
- providing national malaria prevention and treatment;
- HIV combination prevention; and
- introducing microfinance to support the poor to become food secure.

More systemic strategies include

- a coordinated response at national, regional, and country levels;
- development partners continuing to work together;
- finding ways to retain and health personnel to ensure delivery of primary health care;
- sustainable health systems;
- seeking commitment of continued long-term financing of climate change activities; and
- strengthening monitoring, surveillance, and evaluation of public health programmes.

This list is intentionally broad, and yet is not exhaustive. It deliberately takes a health perspective to food security, whereas other food security reports focus on food production. Here the parenting–child health links are prioritized to provide an indication of the breadth of influences that can affect food security and boost resilience to climate change.

Good advances have been made in other sectors over recent years, largely as a result of issues gaining sufficient profile to garner solid investment and multilateral cooperation. Ministers attending the 7th Pacific Health Ministers Meeting in 2007 in Vanuatu called for a Pacific Food Summit. The following year, Pacific Island Forum leaders made food security a priority in the Pacific, and in 2009, Ministers of Trade, Agriculture, and Health endorsed the concept of a Pacific Food Summit at their respective regional meetings. The Pacific Food Summit was held in Port Vila, Vanuatu, in April 2010 and attracted more than 170 people from the 23 countries attending (Food Secure Pacific Working Group 2010). A key to its success was the shared commitment and breadth of involvement. It was genuinely interdisciplinary in nature and included all PICTs. Ministers and senior policy makers from Agriculture, Health and Trade as well as representatives from the food industry, community organizations, faith-based organizations, consumer groups, academia, and regional and national organizations attended. The purpose of the summit was to enable regional action on food security.

More recently, noncommunicable diseases have been identified as a priority issue for joint action among the PICTs. A 2-1-22 Programme has been devised that combines 2 donor organizations, 1 goal, and 22 PICTs to address the shared challenges. There is a clear and urgent need for development of a similar overarching framework for addressing the pressing climate change challenges facing the PICTs. Precedence has been set with these two existing programs, and a framework model of cooperation has been established. The model could be applied to other vulnerable states beyond the Pacific.

Such strategies require significant donor investment to appropriately resource the activities. Neighboring developed countries have international obligations under the UNFCCC to assist developing countries adapt to climate change. The lives of millions of Pacific Islanders, and populations in other vulnerable countries, depend on this international support. The UNFCCC recognizes the special situations of the LDCs and introduced National Adaptation Programme of Action (NAPA). Developed countries that have signed the Kyoto agreement contribute to the fund and manage projects within specific LDCs. Individually funded projects are also beginning to emerge, but the task ahead, especially for the world's LDCs, is enormous and growing.

Many PICTs are progressing their NAPAs, and although the profile of health among climate change strategies has been expanding, there is more to be done. Making the connection between human health and climate change has been slow in the donor organizations. Climate and a changing climate are deeply human issues, as the climate determines the provisioning of human necessities, such as food and water. Climate extremes can destroy these ecosystem services, plus our homes, businesses, and infrastructure, and dismantle sociocultural systems. A healthy population is a key element of adaptive capacity to minimize negative impacts. Therefore, maintaining optimal health determinants; ensuring whole population access to sufficient food, water, clean air, and shelter; and providing equitable access to effective health care and education are the necessary ingredients to securing the health of current and future generations and central to reducing vulnerability to climate change and other shocks.

See also: Ecosystems, Biodiversity, Climate, and Health; Extreme Weather Events.

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WHO; Western Pacific Regional Office (WPRO) – http://www.wpro.who.int/countries/list.htm.

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1.15 Vulnerability and Health: Exploring the Linkages in a Case Study from Southern Africa

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1.15.1 Introduction

Climate and long-term change is increasingly recognized as a critical issue for society, and governments are asking questions about how to allocate scarce resources in order to minimize adverse impacts. A critical component of answering these questions requires an assessment of vulnerability to the changes that are projected to occur. People in Africa are particularly at risk from climate factors, because of exposure combined with low adaptive capacity. In addition, climate coincides with other stressors that affect the livelihoods and well-being of people. On the one hand, long-term changes in weather patterns would bring with it changed health risks, while on the other, the vulnerability of people to climate will be affected by their existing health status.

1.15.2 Vulnerability to Climate

Vulnerability is a contested term that has its origins in the natural hazards and food security literature and is now often applied in climate impacts assessments (Adger 2006). However, an evolution in the understanding of vulnerability has occurred over time. In early impacts assessments, focus was placed solely on the risk of exposure of an ecosystem to a hazard. This meant that impacts assessments at that time would refer to the effects of climate on parameters such as crop production and water availability and could thus be defined as biophysical vulnerability or 'outcome vulnerability' (O'Brien et al. 2007). People were only deemed affected because climate would alter the availability of resources on which they depend for their livelihoods.

In biophysical or outcome vulnerability assessments, there was little recognition of the fact that people are different, and just because they are exposed to the same hazard does not mean they will respond in the same way. 'Social vulnerability' may be defined as the ability to anticipate, resist, cope with, and respond to a hazard (Blaikie et al. 1994). Social vulnerability, in contrast to being seen as an outcome, is viewed more as a potential state of human societies that can affect the way they experience natural hazards (Adger 1999; Adger and Kelly 1999; Blaikie et al. 1994). This potential state is in constant flux, reflecting its dependence on the dynamic interaction of a range of economic and social processes that influence the capacity of individuals, social groups, sectors, regions, and ecosystems to respond to various socioeconomic and biophysical shocks (Leichenko and O'Brien 2002; Comfort et al. 1999). The most vulnerable are those who are most exposed to any changes, who possess a limited coping capacity, and who are least resilient to recovery (Bohle et al. 1994). As the particular mix of structures and institutions is typically context-specific, this has also been labeled 'context vulnerability' (O'Brien et al. 2007). Determining projected climate impacts, therefore, reflects not only likely exposure and biophysical, or outcome, vulnerability (of the ecosystem) but also the social, or context, vulnerability of the people.

Given evidence of differential social vulnerability in the face of hazards or broader environmental risk exposure, a number of studies have tried to characterize the determinants that may give rise to vulnerability (e.g., Pelling 2003; Smith 2001; Blaikie et al. 1994). Vulnerability is a function of economic, social, political, environmental, and technological assets. Who is vulnerable to a hazard is therefore determined by the human and physical forces that shape the allocation of these assets in the society (Pelling and Uitto 2001). Defining vulnerability is also dependent on the scale of analysis (Vincent 2007a).

On the large scale, macro-processes are the most important in determining the distribution and production of entitlements. In the well-developed food security literature, famines have been explained on the basis of entitlement theory (Sen 1981), where the distribution and reproduction of entitlements is dependent on the structural factors of the political-economic environment that can either reduce or precipitate entitlement failure (Downing 1996; Bohle et al. 1994; Watts and Bohle 1993). In the case of food and famine, e.g., the political-economic environment refers to the dominant political system and the way it mediates trade, labor, and markets. In the face of exposure to climate factors, some populations will be able to draw on their entitlements to adapt to the risk, e.g., through awareness and preparation, insurance for losses, and diversifying livelihoods. For example, Adger (1999) shows how collective vulnerability (at community level or higher) to

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extremes in coastal Vietnam is determined by institutional and market structures. In contrast, on the local scale, the role of human agency has a greater influence in access to resources and household-level social status. In such cases, entitlements are socially and spatially differentiated according to factors such as gender, ethnicity, religion, class, and age (Denton 2002; Enarson 2000; Wisner 1998; Cutter 1995).

1.15.3 Climate and Health

Weather patterns, and other aspects of climate, affect human health both directly and indirectly, via biological and ecological processes that influence the transmission of several infectious diseases (McMichael et al. 2003). One of the major health impacts of climate relates to disease burden. The effects of climate on vector-borne malaria and waterborne cholera have been well studied, given that they already pose existing risks in Africa (Boko et al. 2007). Fewer studies have looked at the links between other diseases, such as meningitis, Rift Valley fever, and dengue fever, and climate-related variables (Jansen and Beebe 2010; Anyamba et al. 2009; Cuevas et al. 2007). More indirect effects of climate on health relate to the transmission of human immunodeficiency virus (HIV)/acquired immunodeficiency syndrome (AIDS), heat stress, and respiratory illness, which are discussed here. Other indirect links of climate and health relate to cancer, mental health and stress-related disorders, zoonotic diseases, and food-borne illness (Portier et al. 2010).

1.15.3.1 Direct Climate Effects on Malaria and Cholera

Malaria is the leading cause of mortality and morbidity in hot and humid African countries (Wandiga et al. 2010). The spread of malaria within Africa is dependent on the susceptibility of the vector (mosquitoes of the *Anopheles* genus) and parasite (*Plasmodium falciparum*) to climate. A close association between malaria epidemics and climate has been contested, but a recent paper that analyzes past climate (temperature and precipitation), hydrological and health data (1961–2001), and socioeconomic status of communities from the East African highlands confirms the link between climate and the incidence and severity of malaria epidemics (Wandiga et al. 2010).

In the absence of good epidemiological information, the association of malaria with seasonal climate patterns is used to map risk areas (climatic suitability for endemism), as in the MARA (Mapping Malaria Risk in Africa Project) model (Grover-Kupec et al. 2006; based on baseline endemism maps from Guerra et al. 2008). A global map of *P. falciparum* malaria endemism shows that of the 1.38 billion people at risk of stable *P. falciparum* malaria, 0.66 million are found in Africa, Yemen, and Saudi Arabia (a proportion similar to those found in south and central Asia). High endemism was also widespread in the African region, where 0.35 billion people are at this level of risk, with 0.20 billion at intermediate risk, and 0.11 billion at low stable risk (Hay et al 2009; based on the MARA data, which includes over 7000 *P. falciparum* parasite rate surveys from around the world).

Since malaria is endemic in much of Africa, changes in climate factors affecting malaria may induce an increase in transmission on the fringes of stable zones, e.g., at higher altitude in the highlands (see, e.g., Tonnang et al. 2010). Additional population at risk from malaria is projected in East Africa (Chaves and Koenraadt 2010; van Lieshout and Kovats 2004), while parts of the northern Sahel may have a decreased risk (Caminade et al. 2011). Adverse effects of malaria spread into new regions are typically higher than where the disease is already prevalent, because of the lack of protective genetic modifications that bring immunity. This applies to morbidity and mortality in both children and adults, as shown by the outbreak of epidemics in the East African Highlands (Lindsay and Martens 1998). In Rwanda, the February 1998 malaria epidemic led to a fourfold increase in malaria admissions among pregnant women and a fivefold increase in maternal deaths due to malaria (Hammerich et al. 2002).

The risk of cholera has been shown to increase with increased temperature and rainfall (e.g., Trærup et al. 2010) and with increased sea surface temperature (Paz 2009). Analyses of precipitation, temperatures, and hydrological characteristics of selected stations in the Lake Victoria Basin show that cholera epidemics are closely associated with El Nino years, and epidemics are also triggered by sustained temperatures high above normal ($T_{\max}$) in two consecutive seasons, followed by a slight cooling in the second season (Olago et al. 2007). A global analysis of cholera data from 1974 to 2005, however, showed that while cholera outbreaks demonstrate seasonal patterns in higher absolute latitudes, closer to the equator cholera outbreaks do not follow a clear seasonal pattern (Emch et al. 2008).

1.15.3.2 Indirect Climate Effects on HIV/AIDS, Heat Stress, and Respiratory Illness

In Africa, an important public health issue is the prevalence of HIV/AIDS. There are also interlinkages between climate and HIV/AIDS, although the pathways are less direct than with vector-borne and waterborne diseases. Climate-related factors might increase the risk of HIV/AIDS through its impact on food (in)security and migration. In Malawi, farmers in two districts at high risk of droughts and floods—Nsanje and Salima—observed how the lack of food and limited income to buy food encouraged women to engage in transactional sex as a coping mechanism, thereby increasing their exposure to HIV infection (Action Aid 2006). Migration is also a common coping mechanism in response to local crisis, which may be precipitated by climate extremes and can also increase exposure to HIV infection (Lurie 2004).

In addition to altering the nature and type of risk of particular diseases, long-term changes in temperature might also affect heat-related illnesses. If temperatures were to increase over Africa, as projected, diseases may expand their reach and death tolls, with more indirect effects on water and food security (Costello et al. 2009). These indirect effects of climate could bring about not only mortality and morbidity but also adverse impacts on the well-being, health, and productivity of working populations (Bennett and McMichael 2010).

Temperature also plays a role in the prevalence of many respiratory diseases, and thus it is not surprising that climate affects these diseases, such as tuberculosis, asthma, and allergies. Although climate has less influence on tuberculosis mortality than some other factors, evidence that warm, damp climates are associated with relatively high tuberculosis mortality dates from the early twentieth century (Morland 1936). The burden of tuberculosis in Africa is high, and there is often coinfection of tuberculosis (*Mycobacterium tuberculosis*) and HIV (Dye et al. 1999). Allergies affecting the respiratory system and asthma can also be affected by changes in climate, which in turn affect the load of airborne allergenic pollens (Ariano et al. 2010; Shea et al. 2008). Both heat-related and respiratory illnesses will have differential effects on vulnerable subpopulations, such as children (Bunyavanich et al. 2003).

1.15.4 Health and Vulnerability to Climate

The relationship between climate and health status is two-way: climate affects disease burden and the health status of the population affects (social) vulnerability to climate impacts. Social vulnerability is a potential state of human societies that can affect the way they experience climate parameters and hazards (Adger 1999; Adger and Kelly 1999; Blaikie et al. 1994). People living with poor health are likely to have greater social vulnerability when exposed to climate threats. This is exacerbated by any long-term change in the average climate of a region, which, unlike extreme events, means that populations will not necessarily have a chance to recover and reduce their vulnerability levels before the next exposure.

Reflecting the chronic nature of the health issue and its widespread prevalence across the continent, in Africa it is HIV/AIDS that has most been studied as the health condition that intersects with vulnerability to climate. It has been shown that the transition to a market economy and the introduction of HIV into the human environment has led to institutional decay in some countries, which, as a result, are more likely to suffer from climate-related health issues (Bloom 2004). Infection by HIV/AIDS makes people more vulnerable to climate threats, as sufferers are less able to cope with reduced food intake and have reduced flexibility in livelihood strategies required to adapt.

Furthermore, for people already suffering from HIV/AIDS, exposure to extreme events such as floods can lead to cholera outbreaks, as they are more susceptible. Similarly, any resulting damage to health infrastructure (including home-based care) may impede their access to antiretrovirals. A study of child malnutrition in relation to the HIV epidemic and drought (crop years 2001–02 and 2002–03) in six countries of southern Africa found a strong correlation between HIV and drought and concluded that the combined effects of droughts and HIV/AIDS could have an even more significant adverse impact on child nutrition in the future (Mason et al. 2005).

1.15.5 A Case Study from Southern Africa

This chapter has shown that the impacts of climate are dependent not only on the climate parameters themselves but also on the characteristics of the people who experience those climate parameters and the assets or resources they have with which they can respond to them.

It is essential to determine the impacts on society of possible changes in climate parameters. Traditionally, science has concentrated on projections of long-term changes in climate using models based on past analogs of climate variability, and then made some suggestions as to how such changes might have impacts on human populations through changing patterns of weather and extremes (McCarthy et al. 2001). However, a limitation of such top-down approaches is their failure to take into account the differential vulnerabilities of human populations to those environmental risks, either through resisting an event or by coping once it occurs (Jones and Boer 2003; Stonich 2000). Moreover, the top-down approach provides, at best, just a subset of possible future regional and local climatic conditions, and improvements in modeling bring with them additional uncertainties due to the greater complexity of processes being modeled (Pielke and Wilb 2012; Trenberth 2010). Essentially, as once dominated the thinking with regards to natural hazards, changes in climate are seen as a problem *for* the society, not *of* the society (Hewitt 1997). Many impacts assessments have thus been impeded by only considering one side of the equation—the exposure (Cutter 1996). In reality, assessing the impacts of climate is inextricably linked with an assessment of social vulnerability.

Assessing social vulnerability is thus an essential component of climate impact assessments. A place-based enquiry was undertaken in one community in Limpopo province, South Africa, chosen for its experience of past climate variability and an example of possible future climate change (Vincent et al. 2011; Vincent 2007b). This area, to the north of the Soutpansberg mountains, is semiarid with a summer rainfall season (November–March). There are high levels of interannual variability, punctuated by regular droughts and occasional floods, most notably in 2000. In terms of human characteristics, the village comprises approximately 700 people in 180 households and has a legacy of natural resource-dependent livelihoods (primarily crop farming), in addition to a small level of formal employment in local towns. The area was formerly part of the Venda homeland. An index of social vulnerability to climate has been developed to compare households at grassroots level in Limpopo province, South Africa, and is explained elsewhere (Vincent et al. 2011; Vincent 2007a,b). Health status is incorporated into the index as a recognized driver of social vulnerability, and this element is elaborated on here (Adger and Vincent 2005).

The index is theoretically determined and is an aggregation of five equally weighted component subindices: financial capital, human capital, social capital, physical capital, and natural capital, based on the Sustainable Livelihoods Framework (for more information, see Vincent 2007a,b). While the structure of the index is grounded in the theory of determinants of social vulnerability, the component indicators were chosen as appropriate to the context for which this particular index was first used (a small, dryland village in Limpopo province, South Africa).

Human capital refers to the skills, knowledge, ability to provide productive labor, and good health that allow people to pursue their livelihood strategies and thus meet their livelihood objectives. Human capital is a function of the amount and quality of labor available in the household, which is dependent on factors such as education, health status, and knowledge. In this way, human capital is also a prerequisite for the transformation of natural capital (such as soil and water in agriculture) and physical capital (such as the use of building materials to construct a house) and for the accumulation of financial capital. Accumulation of human capital is also often seen as an end in itself, as illiteracy and poor health are often regarded as core dimensions of poverty, and overcoming them is a primary goal of development. The human capital subindex, e.g., is a composite of two component indicators: household dependency ratio (ratio of working age adults to youth and elderly) and households with a member suffering from a long-term or recurrent disease (Vincent 2007b).

To a certain extent, the progress that South Africa has made in tackling typical rural diseases, such as typhoid and cholera, is offset against the increasing incidence of HIV/AIDS. The disease burden from HIV/AIDS spreads to encompass the entire household, with one study from the Free State province in South Africa finding that people living in a household where at least one person is infected are 3.5 times more likely to have been ill in the last month (Booysen 2002). At the same time, household gross domestic product (GDP) in AIDS-infected households is 19% lower than uninfected households, combined with the increased financial burdens for infected households for medical and funeral expenses (Lewis 2004). Other illnesses would likely have similar effects on household vulnerability, reflecting the same pathways of increased dependence. For that reason, the indicator used to represent this in the demographic structure subindex is a nominal category of whether or not a household has a member who is suffering from a long-term or recurrent illness.

1.15.6 Conclusion

This chapter has provided an overview of the linkages between climate, vulnerability, and health, with a specific focus on southern Africa. Determining the effects of climate parameters on people is dependent on their vulnerability. Initial climate impact assessments assumed that people were passive recipients of global environmental change (i.e., the top-down, outcome vulnerability), only affected insofar as climate affected ecosystems on which they depend. Critiques of this approach posited that people are not all the same, and, in addition to the nature of exposure, their social characteristics (including their health status) mediate how they will experience that exposures and whether it will translate into adverse impacts or not. Moreover, the outcome vulnerability starts with the assumption that changes in regional and local climate statistics can be skillfully predicted, which, as summarized in Preface to this book, is not always the case. A more inclusive assessment of risk can be developed using the bottom-up, contextual vulnerability approach in which the entire spectrum of future possible climates is considered.

Climate factors intersect with health in various ways. The range of many diseases is affected by temperature and rainfall patterns. This includes vector-borne malaria and waterborne cholera, as well as meningitis, Rift Valley fever, and dengue fever. However, the impacts on people again depend on their social vulnerability. At the same time, if more people have a compromised health status, they will likely have a higher social vulnerability to climate. In this way, climate, vulnerability, and health run the risk of negatively reinforcing each other, leading to worse impacts than one alone.

The adverse economic and developmental consequences of climate and disease (and broader suboptimal health status) have been recognized (e.g., Stern 2006; Gallup and Sachs 2001). At the same time, there is evidence to show that focusing resources on addressing climate threats and disease (and suboptimal health status) is beneficial for the economy (and often more cost-effective than dealing with the consequences) (Stern 2006). However, it is essential to begin addressing vulnerability reduction to both climate-related factors and disease in tandem. This is because negatively reinforcing interactions between the two can offset progress made to date. Any change in regional and local climate statistics, e.g., may cause additional risk of contracting malaria faster (through additional exposure) than the existing public health responses are able to reduce it. Increased disease burden, in turn, increases the social vulnerability of people to climate. Ultimately, climate-resilient sustainable development that addresses climate and health risks is the most appropriate way to reduce vulnerability to both risks and the intersecting vulnerabilities that result.

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Volume 2

Climate Vulnerability

Understanding and Addressing Threats to Essential Resources

Volume 2: Vulnerability of Food Resources to Climate

Editor-in-Chief:
Roger A. Pielke, Sr.

Volume Editor:
Dev Niyogi

CLIMATE VULNERABILITY

UNDERSTANDING AND ADDRESSING THREATS TO ESSENTIAL RESOURCES

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UNDERSTANDING AND ADDRESSING THREATS TO ESSENTIAL RESOURCES

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VOLUME 2

VULNERABILITY OF FOOD RESOURCES TO CLIMATE

VOLUME EDITOR

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He has studied terrain-induced mesoscale systems, including the development of a three-dimensional mesoscale model of the sea breeze, for which he received the NOAA Distinguished Authorship Award for 1974. He has worked for NOAA's Experimental Meteorology Lab (1971—74), The University of Virginia (1974—81), and Colorado State University (1981—2006). He served as Colorado State Climatologist from 1999—2006. He was an adjunct faculty member in the Department of Civil and Environmental Engineering at Duke University in Durham, North Carolina (July 2003—06). He was a visiting professor in the Department of Atmospheric Sciences at the University of Arizona from October to December 2004.

He has served as chairman and member of the AMS Committee on Weather Forecasting and Analysis, and was the chief editor for the Monthly Weather Review for 5 years from 1981 to 1985. In 1977, he received the AMS Leroy Meisinger Award for ‘fundamental contributions to mesoscale meteorology through numerical modeling of the sea breeze and interaction among the mountains, oceans, boundary layer, and the free atmosphere’. He received the 1984 Abell New Faculty Research and Graduate Program Award, and also received the 1987/1988 Abell Research Faculty Award. He was declared ‘Researcher of the Year’ by the Colorado State University Research Foundation in 1993. In 2000, he received the Engineering Dean's Council Award from Colorado State University.

He authored a book published by Academic Press entitled ‘Mesoscale meteorological modeling’ in 1984 with a 2nd edition in 2002, a book for Routledge Press entitled ‘The Hurricane in 1990, a book (coauthored with W.R. Cotton) for Cambridge Press entitled ‘Human impacts on weather and climate in 1995; 2nd ed., 2006, a book (coauthored with R.A. Pielke, Jr.) entitled ‘Hurricanes: Their nature and impacts on society’ published in 1997 by John Wiley and Sons, and was co-chief editor (with R.A. Pielke, Jr.) of a book entitled ‘Storms’ published by Routledge Press in 1999.

He was elected as a fellow of the AMS in 1982 and fellow of the American Geophysical Union in 2004. From 1993—96, he served as editor-in-chief of the US National Science Report to the IUGG (1991—94) for the American Geophysical Union. From January 1996 to December 2000, he served as co-chief editor of the *Journal of Atmospheric Science*. In 1998, he received NOAA's ERL Outstanding Scientific Paper (with Conrad Ziegler and Tsengdar Lee) for a modeling study of the convective dryline. He was designated a Pennsylvania State Centennial Fellow in 1996, and named the Pennsylvania State College of Earth and Mineral Sciences Alumni of the year for 1999 (with Bill Cotton). He is currently serving on the AGU Focus Group on Natural Hazards (August 2009—Present) and the AMS Committee on Planned and Inadvertent Weather Modification (October 2009—Present). He is among one of three faculties and one of four members listed by ISI Highly Cited in Geosciences at Colorado State University and the University of Colorado at Boulder, respectively.

He has published over 370 papers in peer-reviewed journals, 55 chapters in books, coedited 9 books, and made over 700 presentations during his career to date. The listing of papers can be viewed at the project website: http://cires.colorado.edu/science/groups/pielke/pubs/. He also launched a science weblog in 2005 to discuss weather and climate issues. This weblog was named one of the 50 most popular Scienceblogs by Nature Magazine on 5 July 2006 and is located at http://pielkeclimatesci.wordpress.com/.

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Dr Jimmy Adegoke is an award winning climate scientist whose research focuses on understanding the relationships between changing land surface processes and diverse indicators of environmental change. His recent work focuses on societal impacts of environmental change including air pollution studies in rapidly changing midlatitude urban areas and climate impacts on water resources in the Lake Chad Basin. He teaches at the University of Missouri-Kansas City (UMKC) where he served as chair of the Department of Geosciences from 2008—10. From August 2010 until very recently, he was Executive Director of the Council for Scientific and Industrial Research (CSIR) Natural Resources and Environment (NRE) Division, Pretoria, South Africa where he also served as the Director of the Applied Center for Climate and Earth Systems Science (ACCESS), a Center of Excellence (CoE) of the South Africa Department of Science and Technology (DST) Global Change Grand Challenge (GCGC) program. He is a member of several professional societies including the American Geophysical Union (AGU), Association of American Geographers (AAG), and American Meteorological Society (AMS). He is on the advisory council of the African Association for Remote Sensing of the Environment (AARSE) and also serves on the technical advisory committee of several United Nations applied science programs, including the United Nations Educational Scientific and Cultural Organization (UNESCO) crosscutting project on the application of remote sensing for water resources and ecosystem management in Africa. He lives in Kansas city where he served a 3-year team as an appointee of the Mayor of Kansas City Missouri (KCMO) on the city's Environmental Management Commission (EMC).

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Dr Dev Niyogi is an associate professor with joint appointment in the Departments of Agronomy and Earth, Atmospheric, and Planetary Science at Perdue University.

He is also the State Climatologist for Indiana and Director of the Indiana State Climate Office. His research seeks to advance the understanding of vegetation and land surface processes in environmental, weather forecasting, and climate analyses, using a combination of dynamical models and surface, satellite remote sensing, and multiscale analysis products.

His research deals with the understanding and representation of the effects of vegetation – land surface processes in environmental processes at different scales. He is one of the three invited, nonfederal representatives to the community modeling effort of the Weather Research and Forecast (WRF) model working group on Land Surface Models, and to the Federal Geophysical Data Commission (FGDC) Spatial Climate Working Group.

He has authored or coauthored 25 successful proposals for external grants totaling over $3M. He vertically integrates undergraduate, graduate, and postdoctoral researchers in his research and is very interdisciplinary in developing collaborative projects.

Dr George Kallos is a professor at the University of Athens, School of Physics, Division of Environmental Physics and Meteorology. He leads the Atmospheric Modeling and Weather Forecasting Group (AM & WFG). He has a BSc from the University of Athens/School of Mathematics (1975). He obtained his MSc (1983) and PhD (1985) in Geophysical Sciences/Atmospheric Sciences Division, Georgia Institute of Technology, School of Geophysical Sciences, USA. He has 110 publications in peer review scientific journals, more than 230 presentations and publications in conference proceedings publications, 10 contributions in books and more than 200 other publications in subjects related to atmospheric physics and chemistry, sea-state conditions, and renewable energy production. He has been invited 70 times to give talks in conferences, seminars, etc. His published work has received >2000 citations. He has participated in 80 projects. He has organized 12 conferences related to air pollution and dust transport in the Mediterranean. He has supervised 10 PhDs and over 100 MSc theses and participated in 20 PhD examinations in Greece and Europe. He is an associate editor for the journals: '*Environmental Fluid Mechanics*', '*Advances in Meteorology*', '*International Journal of Geosciences*', '*Atmospheric Pollution Research*', and '*Journal of Aerospace Operations*'. He was awarded the International Union of Air Pollution Prevention Association – IUAPPA award for his work on 'Long-range transport and air quality work in the Mediterranean region'. His current research activities are related to atmospheric, climatic, air pollution, and sea-state model development and forecasting. He focuses in fully coupled modeling systems. The latest model developments are related to nucleation processes in clouds, desert dust cycle and its direct and indirect effects. Research activities related to renewable energy resources (wind, ocean, solar) are focusing on high accuracy atmospheric model development, energy relationships and predictions, and protection from extremes.

Timothy Seastedt received his BA in biology from the University of Montana, an MS degree in biological sciences from the University of Alaska at Fairbanks, and a PhD degree from the University of Georgia. He was on the faculty at Kansas State University and is currently a professor of Ecology and Evolutionary Biology and fellow of INSTAAR at the University of Colorado, Boulder. Much of his research has been conducted as part of the Long-Term Ecological Research (LTER) programs at KSU and CU. His interests focus on terrestrial ecosystem ecology and the causes and consequences of biotic change. His recent activities have emphasized the ongoing changes found along the grassland to (melting) glacier gradient that exists in the Colorado Front Range.

Katharine Suding received her BA in biology from Williams College and a PhD degree from the University of Michigan. She was on the faculty at University of California Irvine and is currently a professor in Environmental Science, Policy and Management at the University of California Berkeley. Her background is in plant community and ecosystem ecology, with current interests in restoration, resilience, and environmental change.

Faisal Hossain received his PhD from the University of Connecticut in 2004. Prior to that, he had earned his MS and BS from the National University of Singapore and Indian Institute of Technology, Varanasi, respectively. He is currently an associate professor in the Department of Civil and Environmental Engineering where he received one of the highest awards of University – the Caplenor Research Award in 2012. His research interests comprise hydrologic remote sensing, uncertainty modeling of water cycle variables, human modification of extreme hydro-climatology, sustainable water resources engineering, space-borne transboundary water resources management, engineering education, and public outreach. He is also the recipient of awards such as NASA Earth System Science Fellowship (2002), Outstanding PhD Thesis Award (2005), NASA New Investigator Award (2008), American Society of Engineering Education (ASEE) Outstanding Research Award (2009), National Association of Environmental Professionals Education Excellence Award (2010), US Fulbright Faculty Award (2012), G.O.L.D. (Graduate Of the Last Decade) award from University of Connecticut (2012), and American Geophysical Union (AGU) Charles Falkenberg Award. He has published over 85 peer-reviewed journal articles, authored an undergraduate-level textbook, edited two book volumes, and contributed eight book chapters. His recent research on human modification of extreme events by artificial reservoirs has been featured by public media such as the BBC, National Geographic, New Scientist, Newsweek, Fox News, MSNBC, Wired.com, and German Public Radio. He served as an associate editor of *Journal of American Water Resources Association* from 2006–10. Currently, he serves as an associate editor for *Journal of Hydrometeorology* and a lead editor for the water volume of Elsevier Sciences five volume reference series on '*Climate Vulnerability: Understanding and Addressing Threats to Essential Resources*'.

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PREFACE

We are pleased to introduce the five-volume set of books on bottom-up, resource-based vulnerability assessments of the societally and environmentally key resources of water, food, energy, human health and well-being, and ecosystem function. This inclusive bottom-up vulnerability concept requires the determination of the major threats to these resources from climate, but also from other social and environmental issues. After these threats are identified for each resource, the relative risk from natural- and human-caused climate change (estimated from global climate model (GCM) projections, as well as the historical, paleorecord, and worst case sequences of events) can be compared with other environmental and social risks in order to adopt the optimal mitigation and adaptation strategies.

The bottom-up, resource-based approach (referred to by O'Brien (2009) as 'contextual vulnerability') that is the focus of the volume is distinct from the Intergovernmental Panel on Climate Change (IPCC) top-down assessment of vulnerability based on the multidecadal GCM predictions (projections) which O'Brien defined as 'outcome vulnerability' (**Table 1** and **Figure 1**).

An excellent example of the contextual vulnerability is the paper by Romero-Lankao et al. (2012) who concluded in a study of the literature that urban vulnerability is dominated by epidemiological studies and top-down assessments, but that inherent urban vulnerability and urban resilience approaches (the contextual vulnerability) are what is required in order to illuminate a more complete set of drivers of urban vulnerability. They also showed that the large majority of papers on vulnerability use the outcome vulnerability approach. However, as discussed below, this top-down approach has major flaws.

First, there is the issue that the term 'climate' has two definitions. The broader view (and the one adopted by NRC (2005)) is that climate consists of the atmosphere, oceans, land, and cryosphere. This is the preferred usage. The second definition is that climate is the term used for the long-term (e.g., multidecadal) statistics of weather.

As reported in the NRC (2005) report and written in the Pielke et al. (2009) article with respect to human climate forcings.

> In addition to greenhouse gas emissions, other first-order human climate forcings are important to understanding the future behavior of Earth's climate. These forcings are spatially heterogeneous and include the effect of aerosols on clouds and associated precipitation [e.g., Rosenfeld et al. 2008], the influence of aerosol deposition (e.g., black carbon (soot) [Flanner et al. 2007] and reactive nitrogen [Galloway et al. 2004]), and the role of changes in land use/land cover [e.g., Takata et al. 2009]. Among their effects is their role in altering atmospheric and ocean circulation features away from what they would be in the natural climate system [NRC 2005]. As with CO_2, the lengths of time that they affect the climate are estimated to be on multidecadal timescales and longer.

and

> "…the natural causes of climate variations and changes are important, as are the human influences. The human climate forcings involve a diverse range of first-order climate forcings, including, but not limited to, the human input of carbon dioxide (CO2). Most, if not all, of these human influences on regional and global climate will continue to be of concern during the coming decades."

Threats from climate involve any one or combination of climate variables as illustrated in **Figure 2**. There do not, of course, have to be changes in the statistics of these variables to constitute a risk. The term

Table 1 Contrast between a top-down versus bottom-up assessment of the vulnerability of resources to climate variability and change

Approach	*Comparative vulnerability*	*Contextual vulnerability*
Assumed dominant stress	Climate, recent greenhouse gas emissions to the atmosphere, ocean temperatures, aerosols, etc.	Multiple stresses: climate (historical climate variability, land use and water use, altered disturbance regimes, invasive species, contaminants/pollutants, habitat loss, etc.)
Usual timeframe of concern	Long-term, doubled CO_2 30—100 years in the future.	Short-term (0—30 years) and long-term research.
Usual scale of concern	Global, sometimes regional. Local scale needs downscaling techniques. However, there is little evidence to suggest that present models provide realistic, accurate, or precise climate scenarios at local or regional scales.	Local, regional, national, and global scales.
Major parameters of concern	Spatially averaged changes in mean temperatures and precipitation in fairly large grid cells with some regional scenarios for drought.	Potential extreme values in multiple parameters (temperature, precipitations, frost-free days) and additional focus on extreme events (floods, fires, droughts, etc.) measures of uncertainty.
Major limitations for developing coping strategies	Focus on single stress limits preparedness for other stresses. Results often show gradual ramping of climate change-limiting preparedness for extreme events. Results represent only a limited subset of all likely future outcomes — usually unidirectional trends. Results are accepted by many scientists, the media, and the public as actual ‘predictions’. Lost in the translation of results is that all models of the distant future have unstated (presently unknowable) levels of certainty or probability.	Approach requires detailed data on multiple stresses and their interactions at local, regional, national, and global scales, and many areas lack adequate information. Emphasis on short-term issues may limit preparedness for abrupt “threshold” changes in climate sometime in the short or long term. Requires preparedness for a far greater variation of possible futures, including abrupt changes in any direction — this is probably more realistic, yet difficult.

Adapted from Kabat et al. 2004.

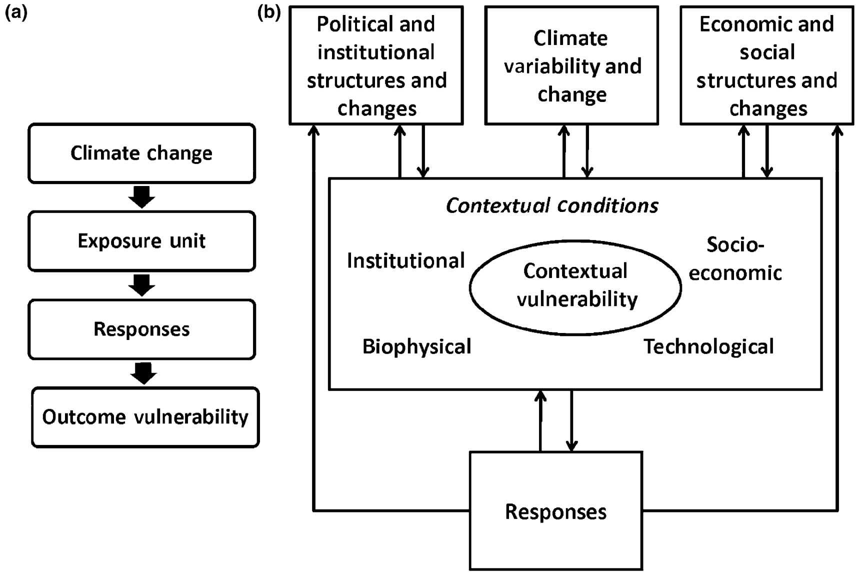
(a)
Climate change
Exposure unit
Responses
Outcome vulnerability
(b)
Political and institutional structures and changes
Climate variability and change
Economic and social structures and changes
Contextual conditions
Institutional
Socio-economic
Contextual vulnerability
Biophysical
Technological
Responses

Figure 1 Framework depicting two interpretations of vulnerability to climate change: (a) outcome vulnerability and (b) contextual vulnerability. *From: Füssel (2009) and O’Brien et al. (2007).*

‘climate change’ should be used to describe any multidecadal or longer alteration in one or more physical, chemical, and/or biological components of the climate system, but as explained below, this terminology has morphed into multiple, diverse (and often mutually exclusive) definitions as used by the impacts communities.

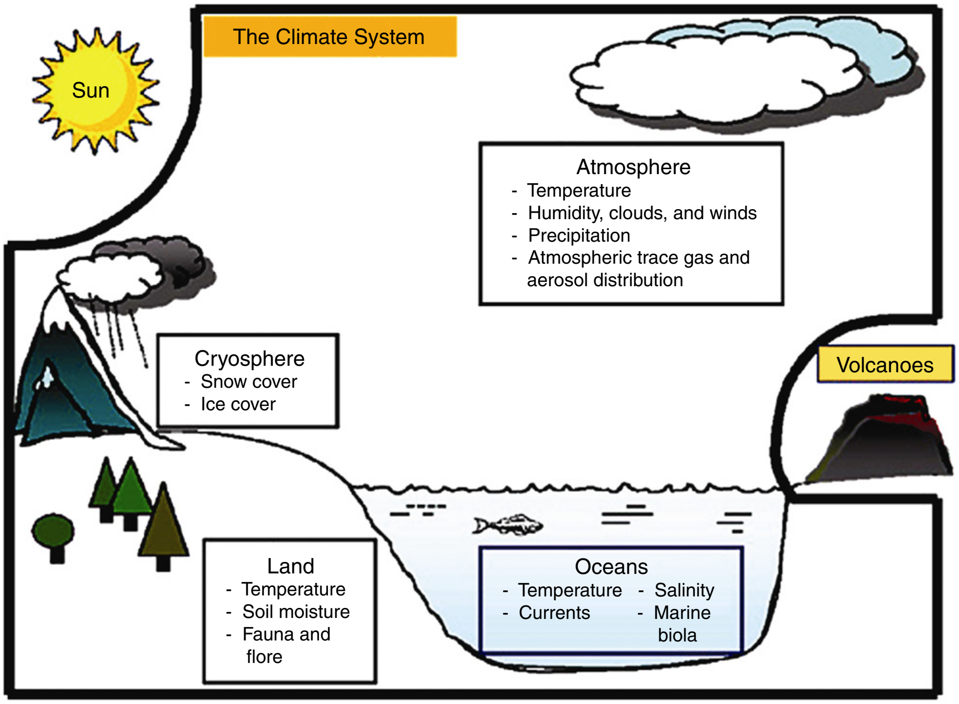
The Climate System
Sun
Atmosphere
- Temperature
- Humidity, clouds, and winds
- Precipitation
- Atmospheric trace gas and aerosol distribution
Cryosphere
- Snow cover
- Ice cover
Volcanoes
Land
- Temperature
- Soil moisture
- Fauna and flore
Oceans
- Temperature
- Currents
- Salinity
- Marine biola

Figure 2 The climate system, consisting of the atmosphere, oceans, land, and cryosphere. Important state variables for each sphere of the climate system are listed in the boxes. For the purposes of this report, the Sun, volcanic emissions, and human-caused emissions of greenhouse gases and changes to the land surface are considered external to the climate system (NRC 2005).

First, climate is never static (Lovejoy and Schertzer 2012). As written in Rial et al. (2004)

> "The Earth's climate system is highly nonlinear: inputs and outputs are not proportional, change is often episodic and abrupt, rather than slow and gradual, and multiple equilibria are the norm."

The assumption of a stable climate system (e.g., the reason for the use of the terminology 'climate stabilization') in the absence of human intervention is a mischaracterization of the behavior of the real climate system. Humans are now adding to the complexity of forcings and feedbacks, but change has always been a part of the climate system. 'Climate change' is, and always has, been occurring. The added word 'change' is, therefore, redundant.

Moreover, there are additional misunderstandings. 'Global warming', which is an increase in the global annual average heat content measured in Joules, is often incorrectly equated to mean 'climate change'. Global warming, however, is just a subset of "climate change."

The term 'climate change', is also being erroneously used to mean only 'anthropogenic caused changes in climate' from nearly 'static' climatic conditions. Frequently, just the human input of greenhouse gases is assumed to be the reason for 'climate change'. For example, NRC (2010) (Climate Stabilization Targets: Emissions, Concentrations, and Impacts Over Decades to Millennia (2010)) states

> "This new report from the National Research Council concludes that emissions of carbon dioxide from the burning of fossil fuels have ushered in a new epoch where human activities will largely determine the evolution of Earth's climate."

Thus, the recommendations to the authors of the volume (not always accepted) were to replace terminology, such as climate change, climate stabilization, and climate disruption, with accurate terminology. When changes in climatic conditions are discussed, it was requested that the actual climate variables (such as temperature, precipitation, length of growing season) that are being altered, be specified. Phrases such as 'changes in regional and global climate statistics' could also be used.

There is a very fundamental reason to limit the use of 'climate change' by the impacts community. Key societal and environmental resources, such as water, food, energy, ecosystem function, and human health respond to climate, not just to an incremental change in the climatic conditions. As noted earlier, the assumption of a stable climate system, in the absence of human intervention, is a mischaracterization of the behavior of the real climate system.

However, some authors retained the use of the terminology 'climate change'. It was acquiesced as long as there was a significant contribution in their chapter to a broad-based assessment of risk to the key resource they were discussing.

Another misused term is 'global change', when really what is almost always meant is a local and/or regional change in the environmental conditions, including from climate. The accurate terminology should be 'environmental change'. The term 'environmental change' is, therefore, preferred rather than 'global change', as the latter terminology is very much a top-down viewpoint. Almost all impacts on key resources are on the local and regional scale.

We also requested the authors start with the risks and factor in the climate threats after thresholds, etc. were first obtained. This was not done in some chapters, but this information can still be extracted from the text. Obtaining the spectrum of risks first is the more inclusive way to assess threats to key resources, and thus, in the view, to prepare the optimal mitigation and adaptation strategies.

For the climate component of risk, the outcome vulnerability (the top-down) approach relies on skillful weather predictions and analyzes with a regional and a local focus. For weather prediction on time periods of days to a week or two, excellent skillful predictions are available for use in outcome vulnerability assessments. On seasonal timescales, there is also some limited predictive skill to apply to outcome vulnerability assessments, particularly for such well-defined weather events such as an El Niño or La Niña (Castro et al. 2007). However, for decadal and multidecadal predictions little, if any, predictive skill has been shown in hindcast climate model predictions of changes in regional weather statistics beyond what is available to the impacts community via the historical, recent paleorecord and a worst case sequence of weather events.

To illustrate the lack of skill, the conclusions from several papers have been summarized. Fyfe et al. (2011) concluded that

> "….for longer term decadal hindcasts a linear trend correction may be required if the model does not reproduce long-term trends. For this reason, we correct for systematic long-term trend biases."

Xu and Yang (2012) find that without tuning from real world observations, the model predictions are in significant error. For example, they found that

> …the traditional dynamic downscaling (TDD) [i.e. without tuning) overestimates precipitation by 0.5-1.5 mm d-1…..The 2-year return level of summer daily maximum temperature simulated by the TDD is underestimated by 2-6°C over the central United States-Canada region."

The paper van Oldenborgh et al. (2012) report just limited predictive skill in two regions of the oceans on the decadal time period, but no regional skill elsewhere, when they conclude that:

> "A 4-model 12-member ensemble of 10-yr hindcasts has been analysed for skill in SST, 2m temperature and precipitation. The main source of skill in temperature is the trend, which is primarily forced by greenhouse gases and aerosols. This trend contributes almost everywhere to the skill. Variation in the global mean temperature around the trend does not have any skill beyond the first year. However, regionally there appears to be skill beyond the trend in the two areas of well-known low-frequency variability: SST in parts of the North Atlantic and Pacific Oceans is predicted better than persistence. A comparison with the CMIP3 ensemble shows that the skill in the northern North Atlantic and eastern Pacific is most likely due to the initialisation, whereas the skill in the subtropical North Atlantic and western North Pacific are probably due to the forcing."

Anagnostopoulos et al. (2010) report that

> "…. local projections do not correlate well with observed measurements. Furthermore, we found that the correlation at a large spatial scale, i.e. the contiguous USA, is worse than [even] at the local scale."

Stephens et al. (2010) wrote

> "models produce precipitation approximately twice as often as that observed and make rainfall far too lightly…..The differences in the character of model precipitation are systemic and have a number of important implications for modeling the coupled Earth system …….little skill in precipitation [is] calculated at individual grid points, and thus applications involving downscaling of grid point precipitation to yet even finer-scale resolution has little foundation and relevance to the real Earth system."

van Haren et al. (2012) concluded from their study with respect to climate model predictions of precipitation that

> "An investigation of precipitation trends in two multi-model ensembles including both global and regional climate models shows that these models fail to reproduce the observed trends….. A quantitative understanding of the causes of these trends is needed so that climate model based projections of future climate can be corrected for these precipitation trend biases…. To conclude, modeled atmospheric circulation and SST trends over the past century are significantly different from the observed ones."

Sun et al. (2012) found that

> "…in global climate models, [t]he radiation sampling error due to infrequent radiation calculations is investigated …….. It is found that…. errors are very large, exceeding 800 W m^{-2} at many non-radiation time steps due to ignoring the effects of clouds…."

There is an important summary of the limitations in multidecadal regional climate predictions in Kundzewicz and Stakhiv (2010) who succinctly conclude that

> "Simply put, the current suite of climate models were not developed to provide the level of accuracy required for adaptation-type analysis."

Since the top-down outcome vulnerability approach depends on skillful decadal and longer regional and local climate predictions, yet they have shown little if any skill, another approach is needed.

For this reason, the volume set of five books presents an alternate approach – the bottom-up, resource-based outcome (contextual) vulnerability perspective. The goal of the set was to focus on the climate component of stress but also consider, in-depth, other environmental and social threats.

The text of the articles is written at a level that allows undergraduate students to understand the material, while providing active researchers with a ready reference resource for information in the respective field.

The questions requested to the authors address with respect to a specific resource were:

1. Why is this resource important? How is it used? To what stakeholders is it valuable?
2. What are the key environmental and social variables that influence this resource?
3. What is the sensitivity of this resource to changes in each of these key variables? This includes, but is not limited to, the sensitivity of the resource to climate variations and change on short (e.g., days), medium (e.g., seasons), and long (e.g., multidecadal) timescales.
4. What changes (thresholds) in these key variables would have to occur to result in a negative (or positive) response to this resource?
5. What are the best estimates of the probabilities for these changes to occur? What tools are available to quantify the effect of these changes? Can these estimates be skillfully predicted?
6. What actions (adaptation/mitigation) can be undertaken in order to minimize or eliminate the negative consequences of these changes (or to optimize a positive response)?
7. What are specific recommendations for policymakers and other stakeholders?

There are also overview chapters that discuss the science of the resource.

Several authors insisted on focusing on the use of the outcome vulnerability (top-down) approach based on the multidecadal GCM projections (statistically or dynamically downscaled) as the starting point of their chapters. The chapters were accepted, despite this shortcoming, because when they finally discussed adaptation in their text, they did present the broader-based bottom-up focus that is the centerpiece of the volume. Readers,

however, need to be aware that the top-down, GCM scenarios are only a subset, at best, of what is plausible in the coming decades. Multidecadal predictions of changes in regional and local climate statistics have not shown skill when run in a hindcast mode for the past several decades.

In summary, the goal of the five-volume set of books is to document the value of a bottom-up, resource-based assessment of risk to key resources, as illustrated schematically in Figure 3a—e. Most, but not all, authors accepted this framework. This can be assessed without having any predictability on

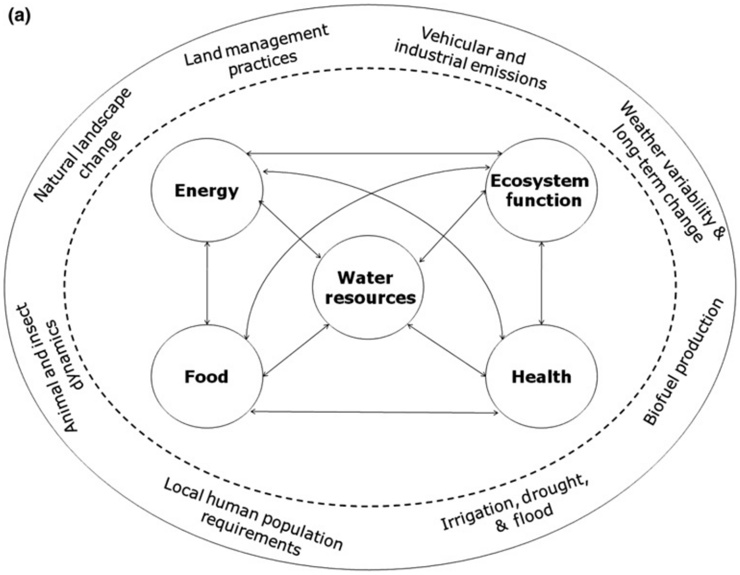
(a)
Land management practices
Vehicular and industrial emissions
Natural landscape change
Weather variability & long-term change
Energy
Ecosystem function
Water resources
Food
Health
Animal and insect dynamics
Biofuel production
Local human population requirements
Irrigation, drought, & flood

Figure 3a Contextual vulnerability for water resources (Hossain: Editor)

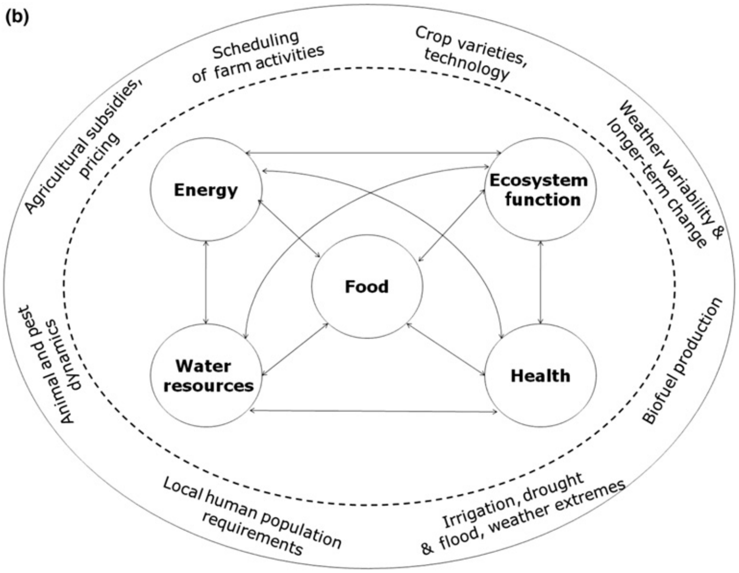
(b)
Scheduling of farm activities
Crop varieties, technology
Agricultural subsidies, pricing
Weather variability & longer-term change
Energy
Ecosystem function
Food
Water resources
Health
Animal and pest dynamics
Biofuel production
Local human population requirements
Irrigation, drought & flood, weather extremes

Figure 3b Contextual vulnerability for food (Niyogi: Editor).

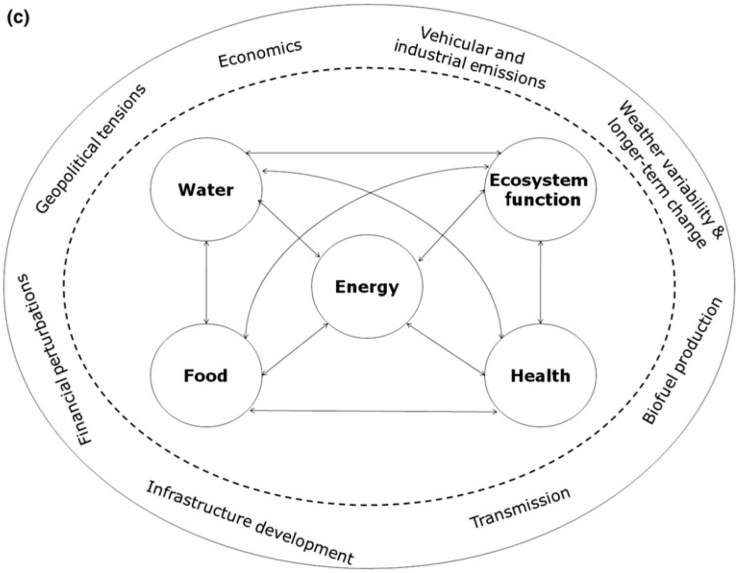
(c)
Economics
Vehicular and industrial emissions
Weather variability & longer-term change
Biofuel production
Transmission
Infrastructure development
Financial perturbations
Geopolitical tensions
Water
Ecosystem function
Energy
Food
Health

Figure 3c Contextual vulnerability for energy (Kallos: Editor).

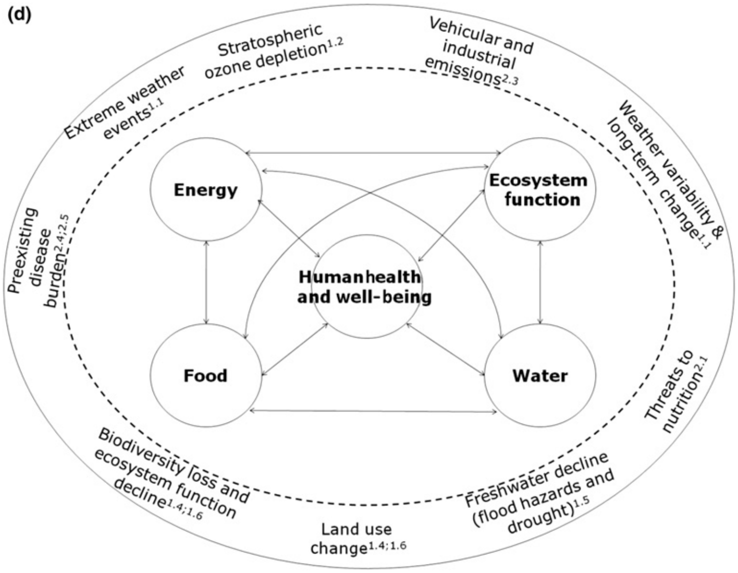
(d)
Stratospheric ozone depletion$^{1.2}$
Vehicular and industrial emissions$^{2.3}$
Weather variability & long-term change$^{1.1}$
Threats to nutrition$^{2.1}$
Freshwater decline (flood hazards and drought)$^{1.5}$
Land use change$^{1.4;1.6}$
Biodiversity loss and ecosystem function decline$^{1.4;1.6}$
Preexisting disease burden$^{2.4;2.5}$
Extreme weather events$^{1.1}$
Energy
Ecosystem function
Humanhealth and well-being
Food
Water

Figure 3d Contextual vulnerability for human health and well-being (Adegoke and Wright Editors).

multidecadal time periods. It is an alternative (and more inclusive) perspective than the IPCC top-down outcome vulnerability approach which starts with the GCMs as the overarching framework. In the bottom-up approach, the scenarios from the GCM predictions should only enter after the specific threats to the resources are determined and even then, they provide, at best, a limited set of insights into what is possible.

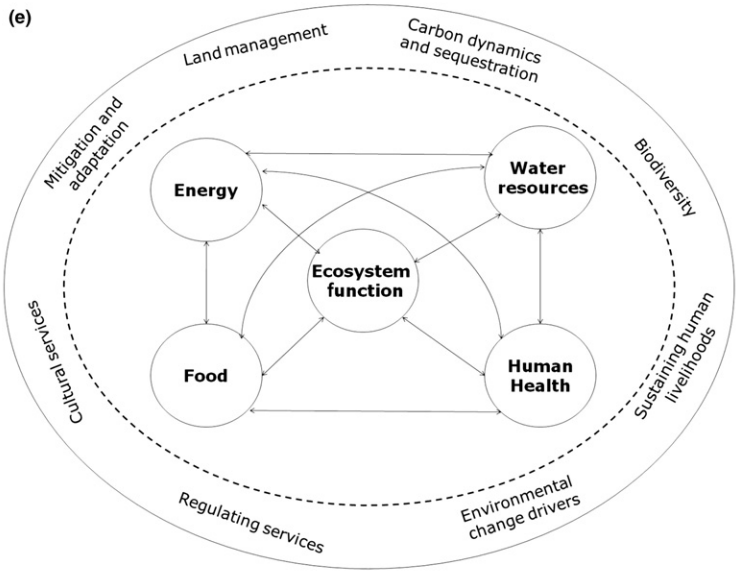
(e)
Land management
Carbon dynamics and sequestration
Biodiversity
Sustaining human livelihoods
Environmental change drivers
Regulating services
Cultural services
Mitigation and adaptation
Energy
Water resources
Ecosystem function
Food
Human Health

Figure 3e Contextual vulnerability for ecosystem function (Seastedt and Suding; Editors).

We look forward to feedback from the readers.

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Jimmy Adegoke,
Faisal Hossain,
George Kallos,
Dev Niyogi,
Timothy Seastedt,
Katharine Suding,
Caradee Y. Wright and
Dallas Staley

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Preface - Vulnerability of Food Resources to Climate

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Agriculture as an enterprise is at a crossroads of increasing productivity and demand. Food security continues to be one of the top problems facing the growing world population. The issue is becoming critical as crop yields and animal productivity rates are flattening or decreasing in some cases and the demand for agricultural product continues to increase. A number of assessments have shown that technology, regional practices, and regional climate hold the key for enhancing and sustaining agricultural productivity. The interplay between agriculture and climate has been well known since prehistoric times. Throughout the rise of civilization, locales and climates suitable for agriculture have been highly coveted and became seats of economic development. At present, there are several breadbasket regions, such as the US Corn Belt, that carry the bulk of global production demands. Additionally, there are pockets of areas throughout the world with intense animal agriculture activities dominating the food source for a world with growing economic capabilities.

Agricultural commodities, from crops to animals to fruits and vegetables to fisheries are currently at a delicate juncture balancing productivity demands, sustainability, regulations, and climatic vagaries. Regional and global climatic patterns have always had significant shifts in terms of the timing, magnitude, intensity, and rates of meteorological events such as precipitation or high temperature events even in the natural system (Rial et al. 2004; Lovejoy and Schertzer 2012). With increasing human influence on the climatic system (NRC 2005), the corresponding need to assess potential effects on future food security has become urgent.

The traditional way of studying agriculture–climate interactions involves a so-called 'top-down' approach in which different current and future scenarios of regional meteorology are prescribed as input to a crop model and corresponding yield changes are obtained. These changes are then used for providing guidance regarding the potential climate impact on the regional agricultural potential yield and productivity. This approach has been used effectively in many studies and has been integrated with economic and impact assessment studies.

In reality, however, a region's agricultural productivity depends on a number of factors – both climatic and nonclimatic – that can change from one region to another. For example, agricultural productivity can be intimately tied to the region's water availability. In this case, if climate patterns indicate a reduction in rainfall, it is highly likely that corresponding top-down crop model estimates will show a reduction in crop yields. In the real world, a number of factors – such as crop planting dates, crop variety, occurrence of extreme weather events such as late season frost or hail, agricultural subsidies for water irrigation and power, scheduling of farm activities, and regional policies such as subsidies – also can play a first-order role in determining if agricultural yields will increase or decrease. Such a bottom-up, or vulnerability, approach is the focus of this book.

The ensuing chapters look at a cross-section of agricultural entities such as corn and poultry production in regions such as the US Corn Belt and present expert opinions on the various vulnerabilities that may affect agricultural productivity and food security. These chapters seek to provide a perspective and approach for conducting such vulnerability assessments where the climatic component is indeed one of the first-order influences; however, equally important are the identification and discussion of nonclimatic stresses on agricultural enterprise.

These chapters provide a cross-section and are only an exemplar of the different regions and approaches one can use in conducting these studies using the vulnerability approach. They also provide a glimpse of the complex problem that is emerging and the corresponding solutions that can be taken to understand and maintain food security.

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2.01 Advances, Vulnerabilities, and Opportunities for Corn: A Perspective from Iowa

RW Elmore, Iowa State University, Ames, IA, USA

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> Cause and effect, means and ends, seed and fruit cannot be severed; for the effect already blooms in the cause, the end preexists in the means, the fruit in the seed.
>
> Ralph Waldo Emerson

2.01.1 Introduction

We stood on the edges of a small winter-wheat field in a highly productive, irrigated area of a developing country. Crop stands were poor, water was limited, and seeding date was late – because it followed late-sown grain sorghum; the farmer expected lower yields for all of those reasons. Three weeks to a month remained before harvest. Many of the nearby fields – along with this one – had numerous wheat varieties seeded in them as evidenced by wildly variable plant height. To cut costs, farmers saved their own seed sacrificing purity and quality and probably yield. Some oat heads even swayed above the wheat canopy mocking the purist in people like me. The farmer when asked his major problems with wheat production, promptly mentioned, or perhaps it was the translator, water, late planting, and climate change – the latter resulting in longer summers, shorter winters. You would think of all the obvious management issues encountered by a farmer in a developing country like this, changes in local and regional climatic conditions would be the least and last of his concern! His focus would revolve around things he could manage: seed purity and quality, weed control, tillage, and so on. But not climate change!

This man recognized the negative impacts of climate. He understood something that most farmers – everywhere in the world – understand well. Crop production hangs on multiple interacting factors and variables a few of which they can control, but most of which they cannot. For this man, the foremost uncontrollable factor was climate. Although certainly a real and perhaps valid concern for farmers like this, a focus on controllable factors of management would produce more fruit.

Although US Corn Belt yields often exceed those of developing countries by 10 times or more, the basic controllable and uncontrollable factors are similar. The 30-year trend line for US corn yields increases at about 2 bu acre^{-1} year^{-1} (125 kg ha^{-1} year^{-1}) (Figure 1). Given that, the 2011 US trend-line yield is 159 bu acre^{-1} (9.98 MG ha^{-1}). Iowa's 2011 trend-line yield is about 177 bu acre^{-1} (11.1 MG ha^{-1}) with a 2.5 bu acre^{-1} increase per year (157 kg ha^{-1} year^{-1}) (USDA-NASS).

The central proposition of this chapter is that genetics, management, and climate have interacted to dramatically improve corn yields over time. The three factors are interrelated, confounded as the flower, fruit, and seed.

In this chapter, I would like to address these questions:

1. What advances contributed to the dramatic US corn yield increases?
2. Where is corn vulnerable relative to climate?

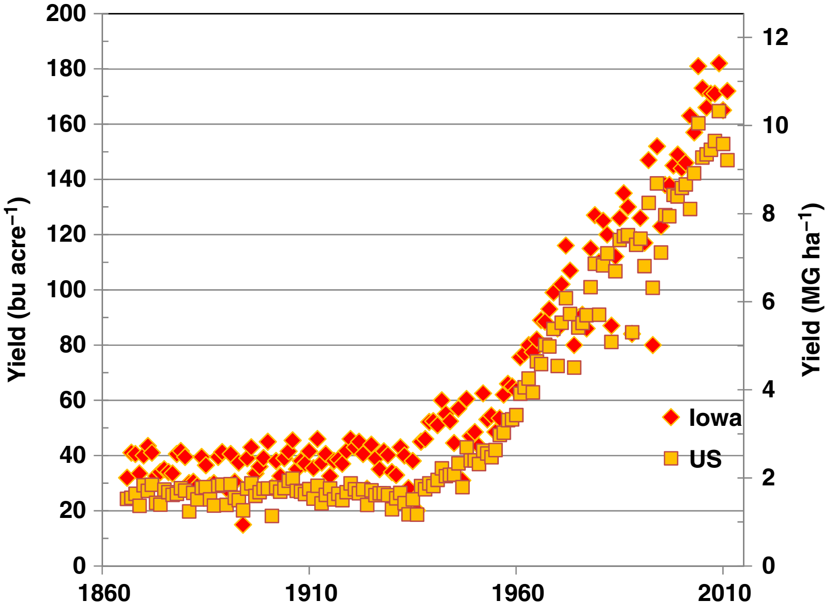

Figure 1 Iowa and US corn yields, 1866–11. Source: Adapted from USDA-NASS, 2011: Crop Production 2010 Summary, http://usda01.library.cornell.edu/usda/current/CropProdSu/CropProdSu-01-12-2011_new_format.pdf.

3. What opportunities – and concerns – exist for corn in the decades to come?

Unless we know where we have come from, we will not know where we are going or, for that matter, how to get there. For this reason, let us examine factors that affected corn production systems over time. This will better enable us to respond well to future needs for change.

2.01.2 Advances in Corn Production in the US Corn Belt

> Throughout history, farmers have adopted new crop varieties and adjusted their practices in accordance with changes in the environment.
>
> (CSSA 2011)

My great grandfather A. G. Mayne farmed at the turn of the twentieth century in north central Illinois. If he were alive today, he would hardly recognize a modern corn field let alone the seeds, hybrids, fertilizers, herbicides, equipment, and other inputs that have collectively allowed the huge increases in productivity displayed in Figure 1. The changes border on dramatic resulting in more than a fivefold increase in corn yields.

Corn is the most widely grown crop in the United States. Iowa sits in the middle of the US Corn Belt and often has more corn acres than any other state with area ranging between 13 and 14 × 10^6 acres (5.3–5.7 × 10^6 ha) (USDA-NASS 2011) per year. Good soils, capable farmers, a viable public research and extension system, and excellent agribusiness resources position Iowa well. A great place to grow corn! Thus, Iowa will serve as a 'case study' along with examples and information from a few other states to address the first question listed above:

> What advances contributed to the dramatic US corn yield increases?

2.01.2.1 Genetics

It never fails; the answer is always the same. When I display charts like Figure 1 to farmer audiences in Extension meetings across Iowa, I ask the question, "So what happened in the 1940s that triggered the rapid increase in corn yields?" After nearly 80 years of yield in Iowa ranging between 30 and 40 bu acre^{-1} (1.88–2.51 MG ha^{-1}), yields abruptly began climbing at about a bushel per acre per year. What happened then? The first response is usually, 'Hybrids!' Indeed that is partly correct, but certainly not independent of other factors. Duvick (2005) attributes about 50% of the increase in corn yields to management and about 50% to breeding. Hybrids without associated improvements in other inputs and practices proved unproductive. With that in mind, let us first look at the dynamic changes in corn genetics over the last nearly century and a half.

2.01.2.1.1 Open-Pollinated Varieties

The ear measures at least 10 inches (25 cm) long and tapers from about 2.5 inches in diameter (6.4 cm) at its base to 2 inches (5 cm) at the tip that gently rounds off, like an Iowa silo. Twenty rows of well-dented kernels with slightly wrinkled tops encircle the dark red cob, each row 54 kernels long. Perhaps it originally held more than a thousand well-shaped large kernels in near-perfect alignment, tightly stacked side-by-side, row-by-row. Some kernels fell off over the years, decades, the last century, actually over the last 105 years. A modern hybrid might contain half that many kernels. Is this an extraordinary ear, yes. A prize winning ear, yes!, the 'Pascal Ear.'

D. L. Pascal of DeWitt, Iowa, entered the ear of Reid's Yellow Dent in the state's grain show, in 1907, the show's best ear. Later the ear was declared "Champion of the America" at the National Corn Show. In contrast to standard practice for the time, not a single kernel from it served for breeding purposes.

In 1908, M. L. Bowman and B. W. Crossley, both Iowa State College (now Iowa State University, ISU) professors, printed a photo of Pascal's ear beside an ear of pod corn as the first figure in their 549 page book titled, *Corn, growing, judging, breeding, feeding, and marketing.* Later, someone mounted the ear vertically on a long screw and placed it in a glass trophy case framed nicely in walnut. At some point, Mrs Pascal presented the ear to ISU where it reportedly remained in the office of the Professor of Farm Crops. I spotted it early last year near the ceiling in an ISU Agronomy Hall office on an almost empty bookshelf, dusty and forgotten – with a note explaining some of what I have mentioned here.

Ears of modern hybrids look like dwarfs in comparison (**Figure 2**). What did farmers and corn breeders believe about the relationship between ear size and yields in 1907? Can you imagine my great grandfather Mayne and his neighbors in north central Illinois hearing about it and perhaps even seeing its picture in Bowman and Crossley's book as they toiled to extract 30 to 40 bu acre^{-1} (1.88–2.51 MG ha^{-1}) with well-bred horses and their home-grown seed corn? Other Corn Belt farmers undoubtedly dreamed of it too. The more math-oriented among them might have thought, "If each of the three seeds check planted into the over 3500 hills per acre (about 8600 per ha) in 42-inch rows (1.06 m) produced an ear like that … just imagine!"

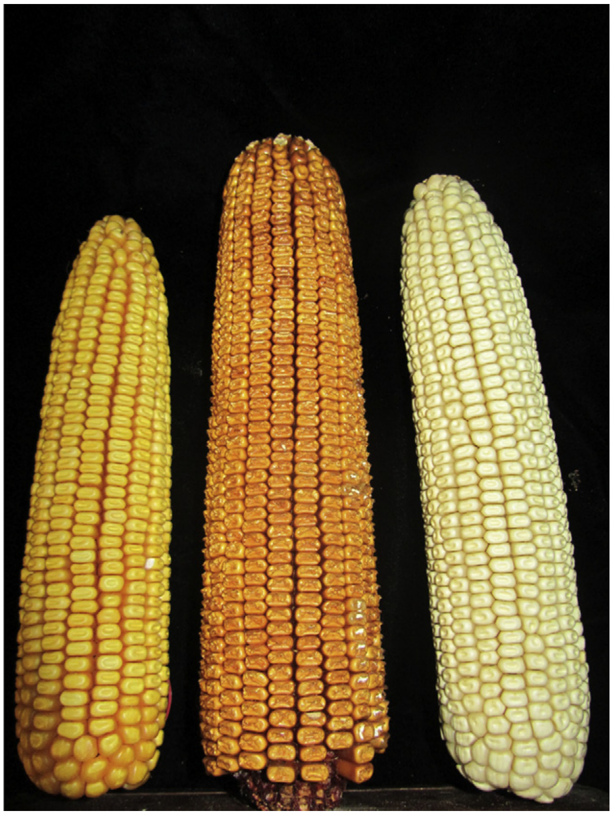

Figure 2 Pascal ear, 1907, center, and modern counterparts.

Seeding rates have astronomically increased since 1907. The Iowa average now hovers right at 30 000 plants acre^{-1} (74.1×10^3 ha^{-1}) and increases about 400 plants acre^{-1} year^{-1} (1000 plants ha^{-1}) (USDA-NASS 2011). A modern field with ears like the one on the left in **Figure 2** might produce 200 bu acre^{-1} (12.6 MG ha^{-1}). The white corn ear on the right in **Figure 2** – from one of our nation's current yield champions – might yield 330 bu acre^{-1} (20.7 MG ha^{-1}) if planted at 35 000 or more seeds per acre (86 400 ha^{-1}). A field with ears like Pascal's ear planted at about 11 000 seeds acre^{-1} might yield 130 bu acre^{-1}, a fabulous yield for 1907 yet far below today's average.

Bowman and Crossley in 1908 wrote that the standard seeding rate was 2–2.5 seeds per hill for 'breeders' growing corn for 'show purposes,' with final stands of 7000–9000 plants acre^{-1} (17.2–22.2 $\times$ 10^3 plants ha^{-1}). Typical farmers then planted three to five seeds per hill. People growing for the corn shows knew then that fewer plants per acre meant bigger ears. Bigger ears, though, do not mean bigger yields.

Henry A. Wallace, as he tried to convince skeptical farmers to grow hybrid corn instead of open-pollinated corn, used to say in reference to corn ear contests, "What do looks mean to a hog?" Wallace thought of corn ear contests as beauty contests which did not represent or – in fact – promote the true genetic yield potential of corn.

One of the foremost reasons corn yields in Iowa and across the United States did not increase until the mid-1940s is that my great grandpa Mayne as well as other farmers and breeders chose seed corn based on ear size and appearance, not yield per acre. Indeed, farmers followed the recommended practice of the day. Corn is cross-pollinated; they initially neither recognized the problems associated with this fact nor the potentials! Sprague (1942) summarized corn breeding progress by saying that earlier methods of corn breeding, for example, mass selection, ear to row selection, and varietal hybridization, were "unsuccessful because of inadequate control of parentage." Parentage in open-pollinated varieties can vary from ear-to-ear and from kernel-to-kernel.

2.01.2.1.2 Hybrids

Interestingly, 2 years before the Pascal ear gained national fame, G. H. Shull, working at Cold Spring Harbor, New York, and E. M. East, first working at the Illinois Agricultural College and later at the Connecticut Experiment Station, first experimented with hybridization as a way to improve corn (Crabb 1947; Jenkins 1936). These scientists first discussed their findings in 1908. Farmers, however, continued to grow corn and select the best ears like their fathers before them. Authors like Bowman and Crossley (1908) devoted 13 pages of their book on how to select and store ears and reinforced this practice summarizing data from 39 experiments by stating, "By all means do not omit picking seed corn this fall with the idea that in the spring you will purchase entirely new seed and start in the business right … There is no corn so adapted to a given

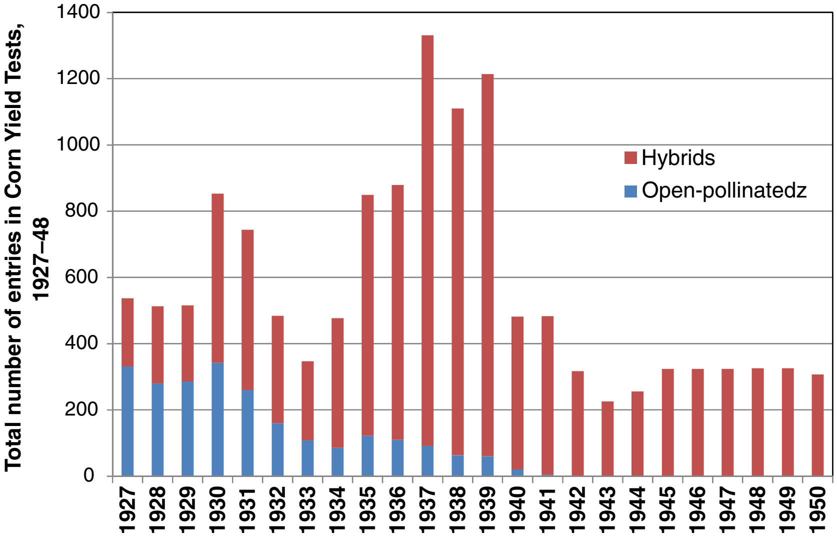

Figure 3 Open-pollinated and hybrid entries in Iowa corn yield tests, 1927–50.

locality as corn which has been successfully grown in that locality for a period of years." They had no doubts, home-grown seed was the 'surest.'

And that indeed was true for a time. Hybrid research began in earnest after Shull and East introduced the idea. In 1913, H. A. Wallace became the first private breeder to use inbreds but did not "… go at it systematically until 1919" (Jenkins 1936). The first hybrids – single crosses – performed poorly relative to open-pollinated varieties. In 1916, D. F. Jones, Connecticut Experiment Station, speculated that crossing two single-cross hybrids could result in more productive double-cross hybrids (Crabb 1947; Jenkins 1936). The innovation of double-cross hybrids changed perceptions on hybrids.

The Iowa Corn Yield Tests conducted across Iowa in the 1920s and 30s (Iowa Corn Yield Tests 1927–2011) were in part responsible for the rapid adoption of hybrids and serves as a proxy for hybrid adoption by farmers. Jenkins (1936) referred to these tests as offering the most extended comparisons of hybrid and variety yields. Hybrids yielded 9.8% more than varieties between 1926 and 1934. The largest yield increase occurred in 1934, 15.2%, which clearly indicated to farmers as well as agronomists that hybrids withstood "abnormally dry conditions of that season better than varieties" (Jenkins 1936). In Nebraska, Stewart et al. (1933) summarized 1927–32 yield contest data by stating that hybrids on average yielded 9% more than varieties and that the five best hybrids out-yielded the five best varieties by 18%.

In 1927, 62% of the entries in the Iowa Corn Yield Tests were open-pollinated varieties; the rest were commercial or experimental hybrids (Figure 3). Six years later in 1933, only 31% of the entries in the trials were open pollinated. By 1942, there were no open-pollinated varieties in the State Yield Tests. Bryan and Jugenheimer reported in 1937 that demand exceeded supply for some high-yielding hybrids. Open-pollinated varieties or inferior hybrids were thus offered as high-yielding hybrids by deceitful salesmen. Ryan and Gross (1950), in a classic sociological study of two Iowa communities, reported that during slightly more than one decade, 1927–41, all farmers in those two communities adopted hybrid corn. According to their report, hybrid corn unlike other innovations, met no organized resistance. However, there were some misgivings. Although hybrids did not affect livestock acceptance, kernels were harder than open-pollinated varieties – it was too 'flinty' – and rumors circulated – but were dispelled – that hybrids were hard on the soil. Farmers were not used to the smaller and less symmetrical ears and smaller kernels of hybrids. Traditional standards for evaluating good corn were challenged.

By 1945, nearly all entries in the Iowa Corn Yield Test (Figure 3) and 99% of Iowa's hybrids were double-cross hybrids; by 1950, 99% of hybrids grown in the United States were double-cross hybrids (Troyer 2004). However, as we initially transitioned from open-pollinated varieties to double-cross hybrids, average yields did not budge much if any at all! Iowa yields hovered around 40 bu acre^{-1} (2.5 MG ha^{-1}) from 1866 until 1942. But something happened around 1942; state average yields rose above 60 bu acre^{-1} (3.8 MG ha^{-1}) for the first time. The trend has not stopped in Iowa: 120 bu acre^{-1} in 1979 (7.53 MG ha^{-1}); 181 bu acre^{-1} in 2004 (11.35 MG ha^{-1}), and 182 bu acre^{-1} in 2009 (11.41 MG ha^{-1}).

Before 1960, double-cross corn hybrids dominated in the Corn Belt (Aldrich et al. 1975). But, in a period of 5 years, double-cross corn hybrids gave way to single-cross hybrids because single crosses were more uniform in plant and ear height and usually higher yielding (Aldrich et al. 1975). One of the first up-right leaved, single-cross hybrids, B73 × MO17 first commercially grown in 1974, proved a land-mark innovation in hybrid history and at its peak may have been accounted for 7–10% of corn grown in the United States (Troyer 2004).

Kiesselbach (1950) summarized his thinking about yield improvements at that time. Regarding hybrids he stated, "… there is no question about their great advantage over antiquated open-pollinated varieties. They have more 'oomph,' better vegetative characteristics, and higher yield." But then he conditioned this by saying, "The best corn hybrids of today with their added productivity of 15–20% owe their high yield in large measure to greater nutritional efficiency, and to disease and insect resistance or tolerance" (p. 29). Little research then supported the need for timelier planting, increased seeding rates, or narrower row spacings.

2.01.2.1.3 Transgenic Hybrids

Transgenic hybrids – hybrids genetically modified with genetic material from other species – first came on the scene in 1995 with the introduction of hybrids with European Corn Borer (*Ostrinia nubilalis*), European corn borer (ECB), resistance. These hybrids had a gene from *Bacillus thuringiensis* (Bt) which encodes a protein toxic to ECB. Later, herbicide resistant and corn rootworm resistant (RW) (*Diabrotica barberi*) hybrids were introduced. In 2011, about two- thirds of US corn contained transgenic traits for either insect resistance or herbicide tolerance or both; Iowa's (USDA-NASS 2011).

But let us be careful in the way we think about transgenic hybrids. Collectively, transgenic hybrids protect yield potential, they do not increase yield potential. They defend against insects and herbicide damage. In other words, in the absence pressure from either insects or weeds, hybrids with and without transgenic protection will perform the same.

Transgenic hybrids have not yet affected yield trends. They were grown on roughly 1/3 of US corn area by 2001. If we use that as a transition point for transgenic hybrid adoption, average US yields since then – from 2001 to 2010 – increased 2.49 bu acre^{-1} year^{-1} (156 kg ha^{-1} year^{-1}) very similar to the previous 10-year period – from 1991 to 2000 – when transgenics were a minor part of our corn production systems where yields increased 2.53 bu acre^{-1} year^{-1} (159 kg ha^{-1} year^{-1}) (USDA-NASS 2011; **Figure 1**). Transgenic hybrid adoption does not appear to have affected yield trends to date. It appears – at least based on these 10-year trends – that prior to transgenic hybrids, farmers were able to limit yield losses to ECB and RW insects and weed competition using a combination of cultural and chemical control options. But be cautious of short-term trends; they are dramatically affected by extremes.

2.01.2.1.4 Hybrid Trait Changes with Breeding Efforts

Hybrid yields have obviously changed since their introduction and mass production; so have various traits or characteristics of the hybrids. Some of these changes have been intentional, other unintentional changes occurred while breeders focused on yield. Some have improved yield and/or stress tolerance, others have had no effect. Duvick (2005) discussed these based on Pioneer hybrids released in different decades of the twentieth century and grown in the same modern environment. **Table 1** lists some of these changes.

Two of the items in **Table 1** deserve a bit of attention here. First, shortening the pollen shed, silk interval is largely responsible for increased stress tolerance of modern hybrids. In scientific papers, this is referred to as ASI, Anthesis – Silk Interval. In modern hybrids it is not uncommon to have silking occurring before pollen shed (Abendroth et al. 2011). A shorter ASI means there is less likelihood of complete pollen shed occurring before silk emergence. Stress has either little effect or may hasten pollen shed timing, but stress delays silk emergence. This shorter ASI insures better 'nick' of pollen shed and silk, reducing barren plants, and increasing kernel set and, thus, grain yield under stress.

Second, the fact that yield potential per plant has not changed over time is significant. Modern hybrids are more stress tolerant than older hybrids as just discussed. Today, one of the major stressors of any given plant is increased plant densities. Modern hybrids are far more able than older hybrids to increase yield per acre because they maintain productivity on a per plant basis in the face of increased stress agents such as increased plant densities (Duvick 2005).

Some have noted that changes in performance resulted with the introduction of single-cross hybrids. According to Troyer (2004), increases in US corn yields during the double-cross era from the 1930s to the 1960s averaged 1.01 bu acre^{-1} year^{-1} (63.3 kg ha^{-1} year^{-1}); he contrasted with trends after the introduction of single-cross hybrids after 1960. From 1960 to 2002, yields increased 1.76 bu acre^{-1} year^{-1} (110.4 kg ha^{-1} year^{-1}). However, these numbers may provide too much initial credit to the early double-cross hybrids. Yields in the 1940s, when the initial double-cross hybrids were grown, increased only 0.89 bu acre^{-1} year^{-1} (55.6 kg ha^{-1} year^{-1}) while those of the 1950s, before single-cross hybrids were introduced, increased 1.85 bu acre^{-1} year^{-1}

Table 1 Hybrid trait changes since the early twentieth century and their impacts on productivity or stress tolerance

Traits that improved grain production efficiency	*'Direction' of changes*	*Unintended stable traits*
Leaf angle	Increased (more upright)	Leaf number
Tassel size	Reduced	Leaf area index
Grain – fill period	Longer	Ears per plant
Grain dry-down rate	Faster	Yield potential per plant
Kernel weights	Increased	
Grain protein	Reduced	
Grain starch	Increased	
Traits that increase stress tolerance and yield	*Direction of changes*	
Tolerance of higher plant densities	Increased yield with higher plant densities	
Leaf rolling with drought	Increases with drought stress	
Pollen shed – silk interval	Shortened	
Barrenness	Increased resistance	
Harvest index	Greater	
Stalk and root lodging	Improved resistance	

Adapted from Duvick, D. N., 2005: The contribution of breeding to yield advances in maize. *Adv. Agron.*, **86**:83–145.

(116 kg ha^{-1} year^{-1} (**Figure 1**)) – very similar to the 1960 to 2010 single-cross hybrid era, 1.89 bu acre^{-1} year^{-1} (118.5 kg ha^{-1} year^{-1}). So although yields during the single-cross hybrid era improved yield trends and yields relative to earlier eras, yield trends for double crosses during the 1950s and those of the single crosses since then are similar.

In addition to these changes in trend lines as we transitioned from double-cross hybrids to single-cross hybrids, double-cross and single-cross hybrids may differ in their responses to environments. According to Troyer (2004), "… it is assumed that single crosses may show greater variation and standard deviations for grain yield across environments than three-way or double crosses. Single cross hybrids are genetically and phenotypically uniform … single crosses can be [generally] susceptible to pests or abiotic factors." Thus, the reduced year-to-year variation in corn yields in the 1950s may be the result of having double-crosses as the predominant hybrid type grown rather than other management or climate-related factors.

No doubt, hybrids substantially improved yields and yield potential. Yet, as Duvick (2005) suggested, only 50% of the yield gains are related to hybrids. Adding hybrid technology alone could not have achieved these fantastic rates of gains; changes in management practices and the environment contributed to the other half of the story. Breeding efforts are confounded with climate and management changes in dynamic ways; breeding occurs over time in ever-changing environments and management.

2.01.2.2 Management

2.01.2.2.1 Planting Patterns: Plant Populations

One of the 'secrets' leading to the 2.0-2.5 bu acre^{-1} (125–157 kg ha^{-1} year^{-1}) increase in Iowa's trend-line yields for the last five to six decades – and similar increases in other states – is that breeders selected hybrid corn for increased yield per acre and not ear size. This resulted in greater stress tolerance as previously discussed in this chapter. Increased plant populations ranks among the more important stress factors.

Comparisons of 'checked' seeding rates with 42 inch (1.07 m) hills in Nebraska tests between 1914 and 1929 showed that stands between 2.5 and 3.5 plants per hill resulted in similar yields (Kiesselbach et al. 1935). Checked planting systems that dominated corn management systems in the Corn Belt through the mid-twentieth century consisted of equidistant spaced hills planted in a regular pattern that allowed mechanical cultivation either parallel or perpendicular to the rows as they were originally planted. By the end of the first half of the twentieth century, Ohio research showed that hybrids could tolerate 2000 plants acre^{-1} more than open-pollinated varieties; that allowed up to four seeds per hill (Kiesselbach 1950). They also recognized then that 15–20% of the seed would not emerge.

During the 1950s breeders made special efforts to produce hybrids suited for higher seeding rates without the risk of lodging and barren plants (Aldrich et al. 1975). Average Corn Belt plant populations in the mid-1970s reached 20 000 plants acre^{-1} with some at 24 000 (49 400 and 59 280 plants per ha, respectively). In the early 1980s, 24 000 plants acre^{-1} maximized yield for the best hybrids; today's hybrids require at least 35 000 plants acre^{-1} (86 450 plants ha^{-1}) for maximum yields (Elmore and Abendroth 2009). Iowa's corn plant populations increase about 400 plants acre^{-1} year^{-1} (USDA-NASS 2011). Modern hybrids withstand stress from higher seeding rates better than ever before.

These two factors – increased stress tolerance with modern hybrids and higher plant populations – are two of the many significant changes in corn management that fueled yield increases over the last half century. Regardless of climate, expect continued increases in seeding rates that maximize yields as breeders select hybrids in nurseries with successively higher and higher plant populations. Corn responses to factors like seeding rates are dynamically linked to climate during the breeding, testing, and selection processes.

2.01.2.2.2 Planting Patterns: Row Spacing

Row spacings varied little during the twentieth century until the 1960s. Prior to 1960, corn was mostly planted in check rows, which allowed for cross cultivation as explained above, with two or more seeds dropped into equally spaced hills. But some corn was 'drilled,' much as we plant today except with much lower seeding rates and wider rows. Comparisons of checked and drilled corn in Nebraska tests between 1922 and 1932 showed that yields were similar, 32.0 and 34.7 bu acre^{-1} (2.0 and 2.18 MG ha^{-1}) for checked and drilled, respectively (Kiesselbach et al. 1935). Drilled planting was a faster operation than check planting; in some situations such as contour farming – for conservation purposes – drill planting was a much simpler operation than check planting (Shedd et al. 1942).

By 1950, the need for 'precise planting' of corn, whether check planted or drilled, was still 'arbitrary' (Kiesselbach 1950); agronomists deemed optimum plant populations more important. For example, 42-inch rows (1.07 m) planted in the hill drop-check pattern were standard for the Iowa Corn Yield Tests from 1927 to 1949. In 1950, row widths in these trials dropped to 40 inches (1.06 m). Both 38- (0.96 m) and 40-inch rows were used in the trials in the 1960s. After that, row widths narrowed to 36 inches (0.91 m) and some to 30 inches (0.76 m) during the 1980s. Today, the yield trials are planted in 30-inch rows.

Thinking about narrow row systems as a way to increase corn yields is not new. Many innovators attempted planting corn in 15- or 20-inch (38–50 cm) rows as early as the 1960s across the Corn Belt. Planting and harvesting equipment were retrofitted for the systems, but, unfortunately, weed control was difficult with herbicides of that era. The system was not widely adopted until much later.

Early on, check-planted corn often out-yielded drilled corn, but it was later understood that weed control accounted for that advantage (Aldrich et al. 1975). Aldrich et al. (1975) also noted that although drilled corn provided more uniform plant distribution, it also increased tillering and lodging more than in checked corn. For these reasons, some farmers continued to check plant as late as 1975.

Row widths continue to decrease across the Midwest (USDA-NASS 2011). The row width reductions were in part due to the fact that yields in the mid-1970s were higher with 'narrow' rows – that is, 30-inch rows (0.76 m) – than wide rows – that is, 40-inch (1.01 m) rows (Aldrich et al. 1975). Current row widths employed by producers typically vary from 15 to 38 inches (0.38–0.97 m), with most Iowa producers planting in 30-inch (0.76 m) rows. Yet, some acres are planted to even narrower row widths. In general, this means 15 inches or 20 inches row widths or twin-row patterns. Twin-row configurations place two rows about 6–8 inches (0.15–0. 20 m) apart on 30-inch centers.

Numerous advantages other than yield exist for reducing row widths including using the same planting equipment for corn and soybean, reduced weed competition, increased shading of the soil, reduced evaporation, increased light interception per plant, and less in-row crowding. Since plant populations continue to increase, narrower rows provide plant placement more similar to equidistant spacing, which, in theory, should improve performance.

In general, greater yield response to narrow rows is expected to occur in northern US corn production areas, likely due to the shorter growing seasons and shorter stature hybrids in those areas. In general for Iowa, corn planted in rows narrower than 30-inches (76 cm) yield the same as those in 30-inch (76 cm) rows largely due to the near complete light interception with modern hybrids and plant populations in 30-inch rows at the key developmental stage of silking. It is important to note, though, that yields are not reduced when using narrow row widths relative to a 30-inch (76 cm) row; they yield the same.

Reductions in corn row spacing over the latter half of the twentieth century and into the early twenty-first century have served to increase yields through capturing more light at silking than is possible with wider rows. Further yield increases associated with narrower rows may not occur until seeding rates dramatically increase and/or plant architecture and, thus, the dynamics of canopy light interception are altered through changes in plant architecture. Changes in local and regional climate conditions would not likely affect these factors.

2.01.2.2.3 Planting Dates

Corn planting occurs earlier than ever before – to no surprise of most Corn Belt farmers and agronomists. Using data provided by USDA-NASS for Iowa, we clearly see that substantial changes occurred over the past three decades. One way to compare across the different periods of time is to look at the date associated with 50% of the acreage planted. For Iowa, the trend to earlier planting is consistent, 50% dates are earlier for each period compared to the previous except for two (1985–89 and 2005–09, the latter 5-year period affected by extremely late planting in 2008 due to wet conditions) (Figure 4). Iowa farmers planted their 2010 corn crop earlier than ever before recorded.

Numerous factors enable producers to plant their acreage earlier and faster. Wider planters with more row units, more cold-stress tolerant hybrids, improved seed treatments, global positioning systems, and reduced tillage systems, have each contributed to this change. As producers farm more acreage (see discussion below), they must naturally start earlier if they want the majority of their corn planted during the optimum planting window for their region (Abendroth and Elmore 2010). This recommendation is based on the fact that producers face a larger yield reduction by planting too late rather than too early.

Planting dates – the second week in May – and harvest dates – third to fourth week of October – of the Iowa Corn Yield Trials varied little from the late 1920s through the late 1960s (Table 2). These data take us back further in time than USDA-NASS data cited above and in Figure 4.

Stable planting dates during the first half of the twentieth century resulted in part due to interacting biological factors: weeds and the insect pest, ECB. Until wide-spread herbicide use, weeds were managed by several preplant tillage operations as well as two or more postemergence cultivations. Planting was delayed until tillage operations were completed and early flushes of weeds controlled. In addition, according to Kiesselbach (1950), ECB invasion affected thinking on the best planting time. Without the pest, anytime in May was suitable. In areas where ECB was a potential threat, Kiesselbach speaking to a national audience suggested a delay in planting until "mid-way in the normal planting season;" many waited until mid-May to start. Farmers and researchers heeded the advice; planting dates varied little over until 1960.

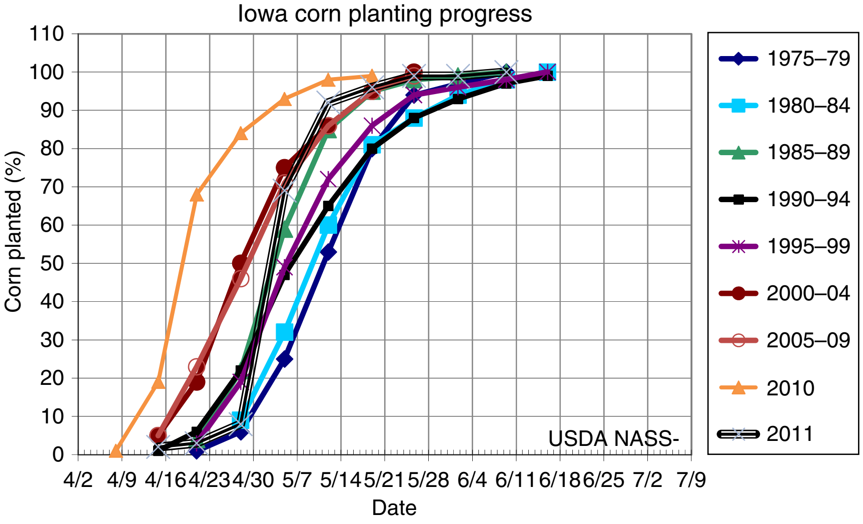

Figure 4 Iowa corn planting progress, 1975–2011. Data compiled from USDA-NASS.

Table 2 Multiyear average planting and harvest dates from Iowa's corn yield trials, 1928–2010

	Multiyear averages		
	Average date of planting	*Average date of harvest*	*Average difference, planting to harvest (days)*
1928–37	10 May	19 Oct	162
1938–47	14 May	27 Oct	166
1948–57	14 May	20 Oct	159
1958–67	13 May	26 Oct	166
1968–77	5 May	20 Oct	168
1978–87	5 May	17 Oct	165
1988–97	4 May	15 Oct	164
1998–07	1 May	10 Oct	163
2001–10	30 Apr	17 Oct	170

Since 1960, both planting dates and harvest dates of the Iowa Corn Yield Trials averaged about 2 days earlier for every 10 years while days between planting and harvest remained fairly consistent over time (Table 2). It is interesting that the period from days of planting to harvest has not dramatically changed in the last 50 years.

However, harvest dates do not represent the effective growing season – the period from planting to crop maturity; the Corn Yield Trials do not report dates of maturity, R6 (Abendroth et al. 2011). Fortunately, the percent of the crop at various developmental stages for Iowa corn 1981 to present are available from USDA-NASS (2011). An analysis of these data indicates that not only are planting dates and harvest dates getting earlier (as also shown in Table 2), but perhaps surprisingly, crop maturity dates are later. Since USDA-NASS records began in 1981, Iowa's effective growing season has increased about half a day every year (data not shown). No doubt these trends reflect the increased grain fill period and faster grain dry down with modern hybrids discussed relative to Table 1.

Early planting dates are expected, desired, and recommended in today's corn production systems. Although the period from planting to harvest is relatively stable, the effective growing season is increasing. Whether these trends in planting dates and growing season are associated with changes in weather patterns is difficult to sort out; again the two are confounded and affected by many other factors that changed during the latter half of the twentieth century and the early twenty-first century.

2.01.2.2.4 Nitrogen Use

Although synthetic N was developed during World War I, widespread use did not occur until after World War II (Paarlberg and Paarlberg 2000) (Figure 5). Indeed, research results from commercial fertilizer use before then were not encouraging. In Nebraska, Stewart et al. (1933) discussed rotations with a legume as essential to maintaining high soil fertility and high yields. They went on to say that "… commercial fertilizers on corn in Nebraska have usually failed to give increased yields sufficient to be profitable" (p. 27). But, in 1949, Nebraska farmers who side-dressed 40 pounds acre^{-1} (45 kg ha^{-1}) nitrogen averaged 60 bu acre^{-1} (3.8 Mg ha^{-1}), while controls yielded 35 bu (2.2 MG ha^{-1}) (Kiesselbach 1950). Iowa nitrogen fertilization experiments began in 1943 (Dumenil 1952). By 1952 in Iowa, N supply for corn came through legumes in rotation, manure, crop residues, and/or N fertilizers (Dumenil 1952). At that time, nitrogen application was in the form of either starter (4-16-8) or side-dress – (ammonium nitrate, urea, etc.). Crop rotation was still the backbone of recommended practices.

Nitrogen use in Iowa did not dramatically increase until the late 1940s. From the mid-1950s through 1975, anhydrous ammonia was the most often used N source (Aldrich et al. 1975). From 1961 to 1980, N sales in Iowa annually increased by over 47 000 tons year^{-1} (42.6×10^3 MG). The trend of increasing N application stalled in 1981 when more than 1.16 million tons (1.05×10^6 MG) were sold. Educational efforts on the part of extension specialists and others in regard to environmental concerns as well as economics, and other forces likely served to level the trend of nitrogen sales for the 1980s until now. Extremes on the recent plateau of N sales include 1983 PIK (Payment in Kind), 1988 drought, and 1993 flooding. 'Payment in Kind' was a 1983 US government program to

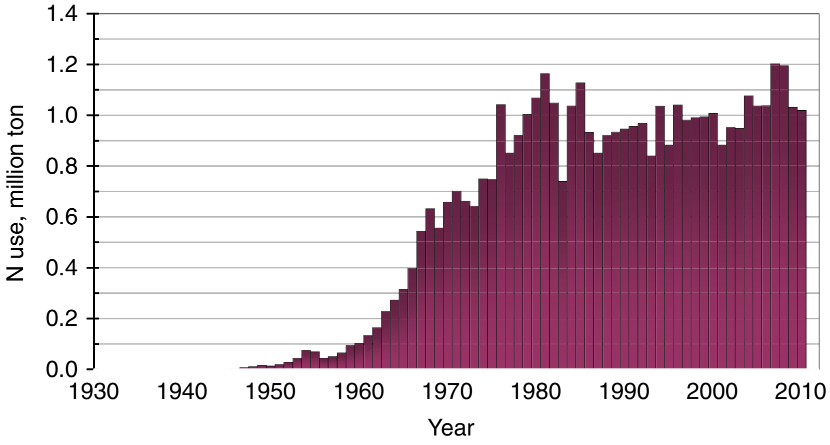

Figure 5 Annual nitrogen sales in Iowa. From John Sawyer, Iowa State University Extension.

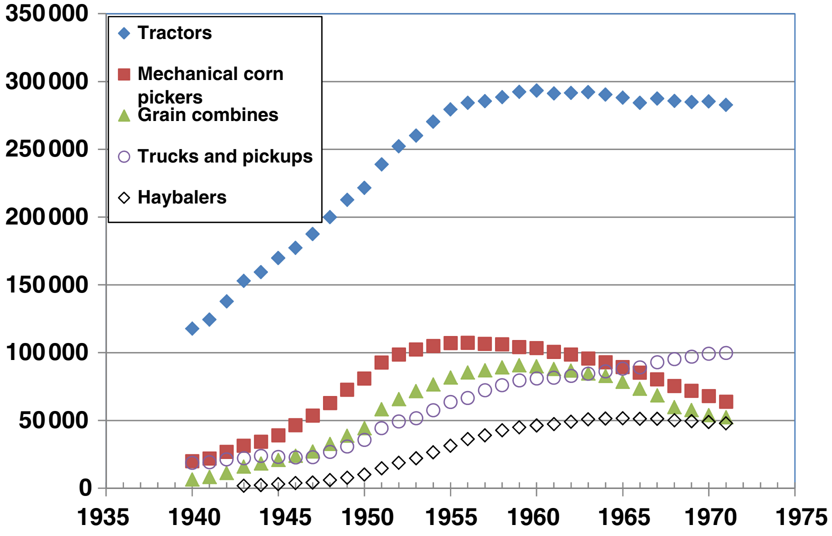

Figure 6 Mechanization of agriculture in Iowa, 1940–71. Numbers of units. Iowa farm census.

help reduce grain surpluses and improve farm income. In the 1983 PIK year, planted corn acres in Iowa fell to below 10 million acres for the first time since 1950.

Nitrogen application affected corn yield trends. From 1950 to 1977, US corn yields increased at a rate of 2.2 bu acre^{-1} year^{-1} (138 kg ha^{-1} year^{-1}). Sinclair and Sinclair (2010) suggest that a cornerstone in the yield increases up to the mid-1970s was the increased supply and application rates of nitrogen (p. 171). They were quick to state that plants genetically suited to take advantage on increased N were developed in tandem with increased N rates. When increases in N application leveled off in the 1980s, so did the rate of corn yield increases. From 1978 to 2010, yields increased 1.9 bu acre^{-1} year^{-1} (119 kg ha^{-1} year^{-1}).

With these trends and the recent plateau in N application in mind, we can rule this as a variable confounded with climate since the early 1980s. However, potential increases in hybrid N-use efficiency (Sinclair and Sinclair 2010) may still result in a confounding of N fertilizer and climate trends.

2.01.2.3 Mechanization and Farm Numbers/Sizes

> Commercial corn production cannot be carried on by hand methods. It can only be done with machinery.
>
> (Shedd et al. 1937)

My great grandfather Mayne was an Illinois farmer, horse, and teacher. In 1904, influenced by his interest in horse-centered agriculture, he said, "I hope the day is far distant when the use of automatic or electrical devices will supersede [the] use [of work horses]." He lived to see the day – which was far distant – when horses were no longer necessary for agriculture to progress. Unfortunately, I was too young to ask what he thought about it.

Mechanization quickly took over the horse power needs of agriculture as great grandfather Mayne feared (Figure 6). Although mechanization was a time saver, it sometimes had drawbacks. According to Shedd et al. (1937), harvesting 70 bu acre^{-1} corn (4.4 MG ha^{-1}) by hand took 9 man hours acre^{-1} (22 h ha^{-1}), whereas it took only 2.5 man hours acre^{-1} (6 h ha^{-1}) with a machine. The down side was that harvest losses were greater with machine than with hand harvest. Those losses were sometimes considerable. Kiesselbach (1950) noted that mounted picker losses with 15% grain moisture were 15%. In addition, 13% of the harvested grain was loose, that is not attached to ears and thus at risk of possible lost in handling and storage (Kiesselbach 1950).

Nevertheless, mechanization saved farmers considerable time and resources. Leonard and Martin (1963) reported that in 1800, a 25 bu acre^{-1} (1.6 MG ha^{-1}) corn crop required 80–90 h of labor per acre^{-1} (200–222 h ha^{-1}), all by hand. By 1870, improved plows and cultivators lowered the labor requirement to 40–70 h acre^{-1} (100–172 h ha^{-1}). By 1890–1910, manual labor requirement was down to about 15 h acre^{-1} (37 h ha^{-1}) with the help of horse-drawn two-row planters and cultivators. By 1945, labor required was 5 h acre^{-1} (12 h ha^{-1}) with machines. Recent innovations in global positioning has allowed a new wave of technology with guidance systems potentially reducing operator fatigue and improving production efficiency perhaps even more than mechanization itself. Since 1945, labor requirements per acre have dropped even more: 1979, 3; 1986, 3; 1996, 1 (Duffy 2009).

Coupled with increased mechanization (at least in Iowa) was a massive decline in farm numbers; farm numbers declined from 215 000 in 1940 to 92 500 in 2010, a loss of about 2100 farms per year (Mike Duffy, ISU, personal communication, 2011). Not only did farm sizes increase but also farmers became more specialized. Early-on, farmers managed multiple crops in diverse cropping systems (corn, soybeans, wheat, oats, alfalfa, clover, etc.) as well as maintaining multiple animal production enterprises (cattle, horses, hogs, sheep, goats, chickens, turkeys, etc.). Today, many Iowa farm operations concentrate on either livestock or crops, with crop-focused farms usually containing only corn and soybeans. Increased farm sizes can result in a subsequent improvement in production efficiency, due to economies of scale, to a certain point beyond which it decreases (Duffy 2009).

Trends to larger farm sizes may ebb a bit based on findings of a recent study using longitudinal agricultural US census data (Melhim et al. 2009). They found that growth rates of large corn farms – as measured by farm income – were less rapid than smaller farms. Corn farms may be reaching or have already reached an equilibrium size. They also found that economies of scale diminished between 1987 and 2002, suggesting that larger farms became less efficient than smaller ones. This supports the comments from Duffy (2009), as previously mentioned. Because of this, Melhim et al. (2009) suggested large farmers approach expansion with caution. Economies of scope for corn producers, however, were similar regardless of farm income; corn farms became less diversified over time because there was little incentive to diversify, that is, to include more crops or products in their operations.

Increased mechanization in farming operations no doubt increased fossil fuel use and CO_2 emissions. But, at the same time, as farmers became more specialized, they improved yields per unit area and increased farm sizes. Recent research suggests increases in farm size may have slowed as just discussed above (Melhim et al. 2009). In any case, increased mechanization has been correlated with increased yields and climate. Correlations do not suggest cause and effect.

2.01.2.4 Weeds, Tillage, Insects, and Diseases

> When tillage begins, other arts follow. The farmers therefore are the founders of human civilization.
>
> (Daniel Webster)

> Weed growth was somewhat more effectively controlled in check-planted corn. … weed control is becoming a more serious problem in Iowa from year to year. … the area of distribution of perennial weeds has been increasing rapidly.
>
> (Shedd et al. 1937)

> Weeds rob the crop of moisture and nutrients.
>
> (Kiesselbach 1950)

2.01.2.4.1 Weed Control and Tillage

Prior to herbicides, the best weed management was tillage, smother crops, poisoning (with certain chemicals), and eternal vigilance among other methods (Shedd et al. 1942). In 1942, E. J. Kraus, University of Chicago, developed 2,4-D, an effective postemergence herbicide for controlling broadleaf weeds (Paarlberg and Paarlberg 2000). Although 2,4-D had proven itself able to control broadleaf weeds without injuring corn by the late 1940s, scientists still considered herbicides as tools to supplement other proven methods of weed control: tillage and crop rotation. There was yet no great interest in preemergence herbicides. Nevertheless, it was understood, at least by some, that, "In most soils, deep plowing is not advantageous and needlessly adds to the expense by way of increased power requirements" (Kiesselbach 1950). By 1963, herbicides were still considered as 'useful supplements' to mechanical weed control and not as complete replacements for it (Leonard and Martin 1963).

The role of herbicides in cropping systems has dramatically changed since 1963. "The nearly complete reliance on herbicides on corn contributed to the developments of current 'conventional cropping systems' that include large-scale production enterprises utilizing high-yielding varieties … and high inputs of chemical fertilizers and pesticides on the most fertile, productive soils available" (Kremer 2004). Certainly though, nearly complete reliance on herbicides resulted in herbicide resistant weeds (Owen 2005).

Reduced tillage systems are now common. As of 2008, tillage systems leaving more than 30% residue on the surface covered 40% of US acres. Another 24% of our tillage systems left 15–30% residue on the surface. Only 36% of the acres were 'conventional till' leaving less than 15% residue (CTIC 2011). No-till and reduced tillage systems depend on herbicides and machines capable of handling large amounts of residue. Reduced tillage systems control both wind and soil erosion and conserve soil moisture. The latter is especially critical in dry years and dry environments.

In the last 50 years, most US corn production systems progressed from using herbicides as 'useful supplements' to herbicides as necessities for most producers. Improved weed control associated with good herbicide management undoubtedly contributed to corn yield increases. Now, weed resistance to herbicides concerns most producers and agronomists. Herbicides allow us to plant corn earlier than ever before permitting us to take advantage of earlier springs.

2.01.2.4.2 Insects and Diseases

Seed disinfectants and protectants in the 1940s improved grain yields in most situations but more so with early planting dates and wet soils, which were not too common (Kiesselbach 1950). Today, virtually all corn planted has seed treatments that control soil-borne insects and pathogens.

In 1935, Paul Müller working with the Swiss company, J. R. Geigy, developed DDT that was widely used by Allied soldiers in World War II. US The farmers recognized the promising role DDT could play in crop production systems and 'quickly expanded its use' (Paarlberg and Paarlberg 2000). Various Bt transgenic insect resistance traits have largely replaced specific insecticide applications.

Postemergence fungicide applications for control of foliar diseases became more common in the last 4–5 years in part due to high corn prices, fungicide availability, and foliar disease pressure. By 2010, 14.6% of the US Corn Belt's 38.6 million acres (15.6×10^6 ha) of corn were treated with fungicides (USDA ERS 2011). Fungicide-use figures were not available in prior USDA ERS reports mostly likely because their use on corn – other than for seed treatments – was negligible prior to 2007.

Fungicides at least in Iowa are often applied to corn after tasseling (VT) in large part to manage the foliar disease Gray Leaf Spot (GLS caused by *Cercospora zeae-maydis*). Although GLS was first identified in Illinois in 1924, prior to 1988 it was not considered economically important although localized outbreaks had occurred (Ward et al. 1999). A dramatic increase in prevalence across the Corn Belt occurred from 1988 to 1995; yield losses up to 50% were reported. Specific corn hybrid vulnerability to GLS was known: a study in the early 1980s found that most Corn Belt hybrids were either highly or moderately susceptible to GLS (Ward et al. 1999).

Moderate temperatures (70–90 °F; 25–32 °C) and prolonged periods of cloudy days, and 12 h of free moisture on leaves with high relative humidity in crop canopies (>12 h at >90% RH) are conducive for GLS epidemics (Rees and Jackson 2008). Since the pathogen survives in crop residue (it is wind borne as well), reduced tillage systems and increased corn following corn in rotation systems have likely contributed to increased GLS problems in the central and western Corn Belt. Increased plant populations reduce airflow in crop canopies and may contribute to this disease.

Disease infections require a susceptible host, the pathogen, and a favorable environment. All of these elements came together 1988–95 spurring the GLS epidemic. Climate may have impacted disease infections.

Advances in Corn Production in the US Corn Belt: Summary

It is incorrect to suggest that increases in corn yield since the 1940s are the result of breeding efforts. Likewise, it is incorrect to suggest that increases in corn yield are the result of climate change – or for that matter improved management practices. The increases are a direct result of multiple factors and events coinciding midway through the twentieth century and continuing to this day. Our challenge – vulnerability – is to continue the trend of increasing yields well into the twenty-first century.

2.01.3 Vulnerabilities

> Changes in temperature, CO_2, and precipitation under the scenarios of climate change for the next 30 years present a challenge to crop production.
>
> (Hatfield et al. 2011)

2.01.3.1 Climate and Impacts on Corn Production

Continuing changes in atmospheric CO_2 concentration, and possible changes in temperature and precipitation, impacts corn production to varying degrees. Doubling CO_2 concentrations from ambient levels in research studies increased corn's leaf photosynthesis by 3% and total biomass and grain yield by 4% (Hatfield et al. 2011). In contrast, the same physiological variables of soybean increased by 35 and 37%, respectively. Corn, like other C_4 photosynthetic pathway crops, responds less to CO_2 increases than C_3 crops like soybeans. Fortunately, C_4 crops are less sensitive to increases in ozone than C_3 crops. Specifically, Hatfield et al. (2011), in their review paper, estimated that an increase in CO_2 from 380 to 440 μmol mol^{-1} would increase Midwest corn yields by 1%. But, increases in CO_2 may also reduce grain protein and increase grain carbohydrates (CSSA 2011). These changes would possibly have negative effects on the livestock industry but positive effects on the ethanol industry. In the latter case, ethanol production stems from kernel carbohydrates. On the other hand, reduced grain protein means that livestock producers will need to supplement grain protein in rations from other sources.

Temperature increases would likely have a greater negative effect on corn than elevated CO_2 itself. Current Midwest temperatures are optimum for corn production while those of the South already exceed optimum (CSSA 2011). Where temperature is the only limiting factor, a temperature of 93 °F (34 °C) is optimum for both vegetative and reproductive growth (Hatfield et al. 2011). For comparison, soybeans perform better in slightly cooler conditions with optimum vegetative development at 86 °F (30 °C) and optimum reproductive development at 79 °F (26 °C). Higher temperatures hasten corn developmental stages. Faster development especially during seed fill means reduced yield potential (Elmore 2010). This effect is compounded when coupled with drought. Pollen viability drops with temperatures greater than 95 °F (35 °C); a temperature of 95 °F (35 °C) reduces kernel growth rate and eventually kernel size compared to a temperature of 86 °F (30 °C) (Hatfield et al. 2011). Hatfield et al. also reported that photosynthetic rates drop above 100 °F (38 °C) and estimate that a temperature increase of 1.4 °F (0.8 °C) will lower irrigated corn yields by 2.5% in both the US Midwest and in the South. When increased temperatures (1.4 °F (0.8 °C)) are coupled with increased CO_2, corn yields in both US regions are reduced by 1.5% (Hatfield et al. 2011). However, Hatfield et al. remind us, "We are in an era of uncharted responses …."

Drought is obviously a major factor in yield variability. One has only to look at corn yields for the drought years of 1983 and 1988 in Figure 1 to recognize this. Increased greenhouse gases could result in more agricultural droughts (Hatfield et al. 2011). In addition, Hatfield et al. note that more frequent high-precipitation events (>2 inches (5 cm) in 48 h) may result in the inability of some soils to rapidly infiltrate water. This inability of some soils will reduce soil moisture available for crops and, thus, encourage the need for cultivars that conserve water and maintain yield (CSSA 2011).

In addition to the impacts on corn, climate affects weeds, insects, and diseases. Increased CO_2 may result in increased weed competition and thus reduced grain yields. In addition to that, Hatfield et al. report that many studies demonstrate declines in pesticide efficacy with higher CO_2. Insect ecology is also affected by temperature while plant pathogens are affected by a combination of temperature, humidity, and precipitation (Hatfield et al. 2011). Warmer less severe winters may increase insect and disease survival over winter (CSSA 2011) although, again, we are in uncharted territory (Hodgson 2012).

To feed our continued population growth, yields must continue to increase, in the face of plausible future climate conditions. Is that possible in corn?

2.01.3.2 Continued Yield Increases? Doubling Yield by 2030?

Subtle changes in tides occur along coastlines in most parts of the world. A necessary line in the sand marks its inevitable rise and fall. Certainly drastic 'sea changes' occur – remember the word Tsunami? I am often asked if the US average corn yield will reach 300 bu acre^{-1} (18.8 MG ha^{-1}) by 2030. For that to happen, a profound transformation, a paradigm shift – a sea change – must occur to reach a national or, for that matter, Iowa state average yield of 300 bu acre^{-1} in less than two decades.

Promises abound for reaching 300 bu acre^{-1} and/or doubling today's yields by 2030. Both producer and general public expectations rise like the tide with these promises. Iowa corn yields are increasing at more than 2 bu acre^{-1} year^{-1} (125 kg ha^{-1} year^{-1}), as previously mentioned, with the 2009 state average at 182 bu acre^{-1} (11.4 MG ha^{-1}) the highest ever recorded. It is possible for the average US corn yield to reach 300 bu acre^{-1} by 2030 but only if the rate of gain is more than tripled from its current increase of 2 bu acre^{-1} year^{-1} (125 kg ha^{-1} year^{-1}) to over 7 bu acre^{-1} (440 kg ha^{-1} year^{-1}) starting now. That magnitude of change seems very unlikely.

Some producers indeed successfully produce very high yields now. The National Corn Growers Association (NCGA) celebrates yield contest winners each year whose corn crops yield from 250 to well over 400 bu acre^{-1} (15.7 to 25 MG ha^{-1}). These top producers with premier environments prove that 300 bu yields per acre (18.8 MG ha^{-1}) are possible with today's genetics coupled with excellent management and environments, but, on a relatively small scale. Few producers have this unique combination of factors.

Unfortunately, a limit to yield may exist. This is a significant concern among agronomists who suggest that top yields of NCGA contest winners stabilized more than 30 years ago (Duvick and Cassman 1999). These elite corn growers with premium environments reported similar yields in the late 1990s as those reported as early as 1985 (370 bu acre^{-1}, 23.2 MG ha^{-1}). However, a recent examination of current yield data from NCGA contest winners suggests that the yields of all first to third place winners since 1988 continues to increase about 2.5 bu acre^{-1} year^{-1} (157 kg ha^{-1} year^{-1}), whereas that of the highest yield in the contest each year increases about 3.7 bu acre^{-1} year^{-1} (232 kg ha^{-1} year^{-1}). These data do not appear to support the hypothesis of a yield ceiling.

Meanwhile, however, recent yields of irrigated NCGA contest winners in Nebraska have leveled off much as Duvick and Cassman (1999) noted more than 10 years ago while yields of dryland contest winners increase at 1.8 bu acre^{-1} year (113 kg ha^{-1} year^{-1}) (data not shown). Nebraska state averages for irrigated and dryland corn producers continue to increase at 2.2 and 1.6 bu acre^{-1} year^{-1}, respectively (138 and 100 kg ha^{-1} year^{-1}, respectively) (USDA-NASS data, trend lines from 1947). The exploitable yield gap between attainable rainfed and irrigated systems is disappearing in Nebraska. Duvick and Cassman's (1999) statement still applies: "The trends … suggest that attainable yield levels in rainfed [dryland] systems … are converging on the attainable yield level of irrigated systems and the later appears to represent a yield ceiling in production-scale fields."

Other corn producers have access to the same genetics as contest winners. Even the best hybrids will produce average yields when coupled with average management and average environments. Solving the yield puzzle will come only with more completely understanding the interaction of these three factors. But wait a minute – aren't dramatic changes being forecast in hybrid development with transgenics? As mentioned above, while transgenic hybrids protect yield, whether herbicide or insect resistant, they do not increase yield potential. A drought gene may add another tool to help protect yield potential, not increase it.

Unfortunately, several forces work to reduce annual yield gains. For example, the current trend for more corn-on-corn – due to market incentives – will pull down averages because of inherently lower yields when corn follows corn in a cropping sequence. With higher prices for corn, less productive soils are brought into production, again lowering average yields. In addition, yield trend increases will likely lessen rather than increase since farmers already use many yield-increasing practices. For example, farmers, in most cases, control weeds and insects better than ever before, and the predominant central Corn Belt row spacing of 30 inches (0.76 m) maximizes yield. Certainly though, continued improvements in weed and insect management as well as other cultural practices are necessary. However, we should expect smaller yield gains from these changes than previously experienced.

We must address increased yield and yield potential from two approaches – both breeding and management. Seed companies focus on breeding and hybrid improvement. Solely trusting on breeding efforts to move yields to the next level is disconcerting. A singular focus on the seed will stymie progress. Dramatic changes in corn yields over the past six decades came from intensive research efforts in both breeding and management, plus a largely favorable environment.

Without a dramatic change (a sea change), US average yields may reach 300 bu acre^{-1} (18.8 MG ha^{-1}) in six decades but may level off at some point before that. That is far behind the pace that numerous groups have promised and many people would like to see.

The slow but consistent increases in the tide of corn yields experienced over the years will hopefully continue; but I cannot say that with confidence. Breeding and management research, and the funds to do it, are necessary. Without this two-pronged approach, the 300 bu acre^{-1} line in the sand will take many decades to reach.

2.01.4 Opportunities and Concerns

Climate effects are not new, neither is the farmer's ability to adapt. Kiesselbach (1950) spent a good deal of a paper presented at the 1950 American Seed Trade Association meetings discussing soil erosion. He mentioned that during World War II the need for maximum total production encouraged bringing marginal lands into cultivation. He stated, "This land should be grass in peace times … One's very soul cries out against the erosion and lack of preventive measures in many fields as one traverses the countryside. On such farms is there not thought of the morrow?" We adapted; in 2008, as previously mentioned, nearly 2/3 of the US had at least 15% residue cover after planting.

By 1950, the highest state average yield recorded was 160 bu acre^{-1} (10 MG ha^{-1}) from both Iowa and Illinois with a normal range of 20–75 bu acre^{-1} (1.25–4.7 MG ha^{-1}) (Kiesselbach 1950). Kiesselbach by 1950 had witnessed an increase in US average corn yields from 26 bu acre^{-1} (1.63 MG ha^{-1}) to a 9-year average of 35 (2.19 MG ha^{-1}) in

1941–49. He predicted an increase of 60% in 25 years; going from 35 bu in the 1940s to 60 bu acre^{-1} (3.76 MG ha^{-1}) by 1975. He would be surprised to see that the combination of all factors increased yields far more than he expected; the 1975 average US corn yield was 86 bu acre^{-1} (5.39 MG ha^{-1}), double the increase from what Kiesselbach expected! How much higher can yields go especially in the light of climate change? I am often reminded, "Don't bet against technology!" (Kendall Lamkey, personal communication, 2011).

Genetic, management, and environmental changes working together – and at times in opposition to each – over the last six decades resulted in incredible unprecedented gains in corn productivity. For these trends to continue, we must focus on breeding for yield – as well as protecting yield, paying close attention to and adapting management practices, and be ever vigilant to subtle barely perceivable changes in local and regional weather patterns.

These three causes interact, together, inseparable, as a seed and its fruit. Let us do our best with what we have, manage what we can, control what we have to – and can – control, with a focus on conducting adaptive research, teaching the best science, extending information, and mitigating and adapting to climate so subsequent generations are prepared to feed themselves.

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2.02 Soybean

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2.02.1 Introduction

The main climate vulnerability that soybean faces in the future is the same one it has been facing since agriculture began – unpredictable and insufficient precipitation. Heavy precipitation events are problematic, and their frequency has been forecast to increase in the future (Meehl et al. 2007; Gutowski et al. 2008), but drought constitutes the greatest threat to soybean and most other crops (Purcell and Specht 2004; Sinclair 2011). Crop production without irrigation is water-limited to a significant extent at present compared with theoretical full potential (Rost et al. 2009). In the future, regions of major soybean production in the United States may experience mild drying during the growing season according to IPCC top-down multi-decadal model projections, due to increased evaporation with higher temperatures (Meehl et al. 2006; Christensen et al. 2007; Dai 2011). Soybean breeding and management strategies appear capable of coping with higher temperatures and longer growing seasons (Sinclair 2011). Rising atmospheric CO_2 concentrations will likely stimulate growth and yield, as well as ameliorate negative impacts of air pollutants such as ozone. Increased frequency of heavy precipitation events is likely to exacerbate runoff, but water deficit at crucial times in the growing season can be devastating. Improving soybean tolerance to water stress and its interaction with heat stress should be emphasized (Purcell and Specht 2004).

2.02.2 Background

Soybean is the major oilseed produced and consumed in the world (Wilcox 2004). Worldwide, soybean is ninth in production tons among crops, with a gross production value of US$79 billion in 2009 (FAO 2009). The largest producers of soybean are the United States, Brazil, and Argentina, accounting for 80% of the world's production (223 million metric ton (MT) in 2009) (**Table 1**) (FAO 2009). China and India produce 11% of the world's soybeans. Expansion of oil crop production has been very rapid in recent decades, which accounts for a large share of the expansion of the world's agricultural land, with a net increase of 75 million ha between 1974–76 and 1997–99. Current production is up from 42 million MT in 1970. Seed yields of soybean have increased about 1% per year in the major soybean-producing countries. Brazil has the greatest potential for expanding soybean production areas (Wilcox 2004).

In the United States, soybean is grown in the eastern half of the country where adequate moisture is available for successful crop production. Soybean production has been made profitable in the Central Plains and mid-south through the use of irrigation (Heatherly and Elmore 2004). The north-central states produce 82% of the total production in the United States (Wilcox 2004). Iowa, Illinois, Minnesota, Indiana, Nebraska, Missouri, and Ohio are leading producers in the northern United States, while Arkansas, Mississippi, and North Carolina are leading producers in the southern states. Soybean is mainly grown as a full-season, spring-seeded crop, although about 9% is planted as a second crop, following winter wheat, rice, or winter canola, south of 35° N latitude (Wilcox 2004).

Brazil's soybean production is concentrated in two main regions, the South and the Center-West (Wilcox 2004). The South has been the historical center of Brazil's soybean production. It includes the states of Parana and Rio Grande do Sul. Center-West includes the states of Mato Grosso, Mato Grosso do Sul, and Goias. The South has semitropical and the Center-West has a tropical climate. Brazil is generally milder and wetter than the United States and temperatures vary little throughout the year. Monthly average temperatures range 17–24 °C in Parana and 23–28 °C in Mato Grosso. Crop production in Brazil and Argentina is about 6 months later than in the United States.

In Argentina, soybean production is mainly in the provinces of Cordoba, Santa Fe, Buenos Aires, and Entire Rios in the

Table 1 Worldwide soybean production in 2009 (metric ton, MT) (FAO 2009)

Country	*Production (MT)*	*Production (%)*
United States	91 417 300	41
Brazil	57 345 400	26
Argentina	30 993 400	14
China	14 981 221	7
India	10 050 000	4
Other	18 397 563	8
Total	223 184 884	

Data from FAO, 2009: FAO Statistical Databases. Food and Agricultural Organization of the United Nations

http://dx.doi.org/10.1016/B978-0-12-384703-4.00204-5

central-eastern region of the country, the Pampas (Wilcox 2004). The region is temperate-humid with an annual mean temperature of 17 °C in the north and 14 °C in the south (Magrin et al. 1997). Mean rainfall varies from 110–130 mm in November to 70–140 mm in April, with considerable year-to-year variation (Penalba et al. 2007).

2.02.3 Warming Temperature

Global-scale and sub-global studies have detected the influence of anthropogenic forcing on the twentieth century near-surface temperature changes that is inconsistent with natural forcings alone (30; NRC 2005), although there is also research that attributes a significant fraction of the observed temperature variations to natural climate forcings (Wyatt et al. 2011). Future climates could therefore be warmer regardless of the cause (Figure 1) (Meehl et al. 2007). By mid-century (2046–65), the magnitude of multi-model globally averaged surface air temperature (SAT) warming is estimated by the IPCC as +1.3, +1.8, and +1.7 °C from the AOGCMs for B1, A1B and A2 IPCC SRES emission scenarios, respectively (Meehl et al. 2007). Geographical patterns of projected SAT warming from these models predict the greatest temperature increases over land (roughly twice the global average temperature increase) (Meehl et al. 2007). Large regional changes that include possibilities of both warming and some cooling are also possible – along with increases in diurnal and longer term variability (Lovejoy and Schertzer 2012).

North American observations show a general increase in the number of warm nights (Gutowski et al. 2008). Growing season length is also increasing. The 1-week increase in growing season length observed over the twentieth century could be 2-weeks longer by the end of the twenty-first century (Gutowski et al. 2008). In a warmer climate, there would also be an increased risk of more intense, more frequent and longer-lasting heat waves (Meehl et al. 2007).

Multiple regression analysis of climate and global soybean yield data for 1961–2002 showed a positive relationship with precipitation and a negative one with warming (Lobell and Field 2007). It was suggested that increased crop development rates, water stress, and canopy respiration could be responsible for the trends observed. Multiple regression analyses showed that soybean in the humid Argentine Pampas was sensitive to a higher maximum temperature during summer months and rainfall excesses in the maturity-harvest period, which resulted in a lower yield (Penalba et al. 2007). A higher minimum temperature during the growing season increased yield. The most significant spatial coherence with yield was seasonal precipitation, which can be considered a proper yield indicator (Penalba et al. 2007).

The growing temperature range (mean daily air temperature) for soybean is 20–30 °C (Allen and Boote 2000). However, low nighttime temperatures (<12 °C) and high daytime temperatures (>36 °C) can limit production (Allen and Boote 2000). Net photosynthesis increases with temperature to about 40 °C (Allen and Boote 2000). In outdoor controlled-environment chambers, whole-canopy photosynthesis rates (and vegetative growth) were maintained at 44/34 °C sinusoidal maximum–minimum (day/night) temperatures (Allen and Boote 2000). Reproductive development is strongly dependent on temperature, with delays to reach pod

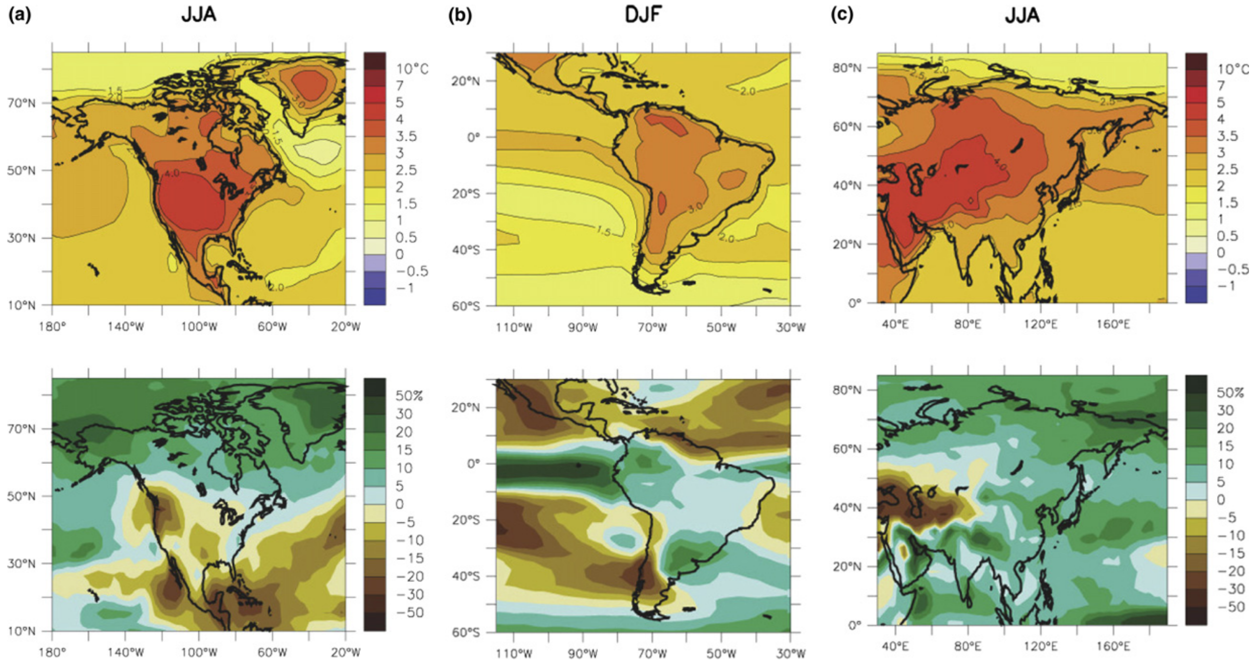

Figure 1 Projected changes in temperature (upper panels) and amount of precipitation (lower panels) during 3 months of the soybean growing season in North America (a), South America (b), and Asia (c) between 1980–99 and 2080–99, averaged over 21 general circulation models (A1B scenario) (Christensen et al. 2007). This is an example of the top-down approach where the vulnerability starts from the multi-decadal global climate model prediction. As such they should be interpreted as, at best, a subset of what is possible in the coming decades. IPCC Fourth Assessment Report, Climate Change 2007 (AR4).

maturity (R7) when mean daily temperatures >31 °C (Allen and Boote 2000). In general, soybean, along with most warm-season seed crops, produces fewer viable seeds as air temperatures increase above an optimum mean daily temperature of about 26 °C (Allen and Boote 2000).

With regard to the effect of warming on soybean reproduction, flowering is flexible. There are three racemes per node, and if flowers abscise due to heat stress, the other racemes can produce blossoms when high temperatures subside. Heat waves per se will not be a threat to seed production, but they can make water stress worse (T.E. Carter, personal communication) – and vice versa; i.e., the heat stress can be worse under water stress. Farmers can adapt to warmer temperatures – seasonally or in the long run – by planting earlier with the appropriate soybean maturity group, as shown by the successful early soybean planting system (ESPS) (see below) (Heatherly and Elmore 2004).

2.02.4 Drought

Studies have concluded that there is an increasing occurrence of hydrological extremes and variability (refs). There are studies that conclude, based on top-down global multi-decadal model predictions, that the future climate is expected to have higher moisture content (Meehl et al. 2007). The increase in water-holding capacity of the atmosphere would likely increase the frequency of heavy precipitation events, as extreme precipitation is constrained by the atmospheric moisture content (Meehl et al. 2007). There is also a trend for increasing dry periods between rainfall events, although models are less consistent about this (Meehl et al. 2011). There has been a long-standing projection by climate models for increased summer drying in the mid-latitudes, with an associated increased probability of drought (Meehl et al. 2007; Dai 2011). Soybean-producing regions in the United States could experience decreased precipitation ranging from 5 to 10% during summer months by the end of this century (Figure 1) (Christensen et al. 2007). Aridity is projected to increase in soybean-growing regions in the Americas (except northeast Argentina and Uruguay) and Southeast Asia due to the effects of regional warming attributable at least in part to anthropogenic greenhouse gas emissions (Dai 2011). Global crop net primary production decreases by 10% with the climate expected with the SRES A2 emission scenario by 2050 due to regional precipitation declines, higher temperatures that lead to higher crop water limitation, and direct crop damage (Rost et al. 2009). Elevated CO_2 offsets these negative effects, but the magnitude of the effect is uncertain. Increased moisture content of atmosphere would dampen the effect of warming on vapor pressure deficit, which increases exponentially with temperature and drives transpirational water loss from plants, but some increase in evapotranspiration may occur nonetheless. However, simulation studies may have overestimated the impact of high temperature on crop water use by not accounting for increases in vapor pressure (Sinclair 2011).

Soybean yield, like many crops, is highly sensitive to water availability, which is mainly determined by precipitation and temperature (Purcell and Specht 2004; Penalba et al. 2007). Interannual variability of soybean yields in Argentina was generally accompanied by interannual variability in seasonal precipitation (Penalba et al. 2007). Higher rainfall anomalies during the maturity-harvest period had a negative impact on yield, possibly related to disease, flooding and failed harvests (Penalba et al. 2007).

Seed yield (Y) has been shown to be related to plant traits and physiology in water-limited environments through the following relationship:

$$Y = T \times \mathrm{WUE} \times \mathrm{HI},$$

where T is the amount of water transpired, WUE is the water use efficiency, and HI is the harvest index (Purcell and Specht 2004). In this relationship, T refers to the total quantity of water transpired by the plant from emergence to physiological maturity. Production WUE refers the relative amount of shoot biomass or seed produced per unit of water transpired. At the physiological level, WUE is defined as the ratio of net photosynthesis to transpiration, also referred to as transpiration efficiency. HI refers to the ratio of grain mass to total shoot mass. Plant traits that increase any of the factors in the above equation have the potential to increase plant yield under water stress conditions (Purcell and Specht 2004).

Studies have focused on a number of genetic, physiological, morphological, and developmental and management approaches to increasing soybean drought tolerance (Purcell and Specht 2004). Yield can be increased in water-limited environments by increasing transpiration. This has been successfully accomplished with the ESPS that is utilized in the mid-south region of the United States (Heatherly and Elmore 2004). Yield losses due to dry, hot late-season conditions in Arkansas, Mississippi, Louisiana, and Texas have been reduced by planting in the spring when precipitation sufficient for crop growth is more likely and cooler temperatures decrease evaporative demand. Early maturing soybean cultivars are used to better match phenology with available water (Purcell and Specht 2004). Minimum tillage and cover crops are also used to increase soil organic matter, which can increase soil volumetric water content and help conserve soil moisture (Purcell and Specht 2004). Deeper rooting assisted by osmotic adjustment of roots to maintain cell turgor, when tissue water potential declines, has promising potential for improving transpiration and yield as well (Purcell and Specht 2004). Improved tolerance to aluminum, which is found in toxic concentrations in lower soil horizons, has been associated with drought tolerance in a slow-wilting genotype. Tolerance to aluminum was correlated with the concentration of citrate in root tips, suggesting that citrate release was involved in aluminum exclusion in tolerant genotypes (Silva et al. 2001). Breeding and genetic modification for this trait may be beneficial.

Improved WUE is expected to occur with increasing atmospheric concentrations of CO_2 because net photosynthesis is higher and transpiration is lower due to reduced stomatal conductance (Allen and Boote 2000). Both factors would contribute to yield increases in soybean. However, reduced transpirational cooling leads to higher leaf temperatures and leaf-to-air vapor pressure deficits, which increases transpiration and respiration, thus decreasing net crop biomass gain. Water stress increased leaf temperature and leaf-to-air vapor pressure deficit in soybean plants (Allen et al. 1994). Management practices employed in ESPS also increase WUE by growing plants when evaporative demand and VPD are decreased by cooler temperatures (Purcell and Specht 2004).

The most sensitive component of soybean biology to drought stress may be nitrogen fixation by symbiotic *Bradyrhizobium japonicum* bacteria in root nodules (Purcell and Specht 2004; Sinclair et al. 2010). Nitrogen fixation is more sensitive to water deficit than many other processes, including photosynthesis, biomass production, transpiration, and nitrogen uptake from the soil (Purcell and Specht 2004). Increased concentrations of nitrogen compounds (ureides) in water-stressed plants suggested that nitrogen fixation is inhibited by feedback regulation of nitrogenase activity in the nodule (Serraj and Sinclair 2003). Factors that decrease nitrogen supply to soybean invariably impact seed yield because the high protein concentration of soybean grain requires a large amount of nitrogen. Prolonging nitrogen fixation during water stress could prevent premature senescence and improve HI, thereby increasing yield (Sinclair et al. 2010). This is a particularly attractive trait for improvement.

2.02.5 Atmospheric CO_2

Atmospheric concentrations of CO_2 continue to rise due to increasing use of fossil fuels, biomass burning, and cement manufacturing. Rising concentrations of atmospheric CO_2 stimulate biomass and yield production of soybean (Allen and Boote 2000; Ainsworth et al. 2002). Elevated CO_2 also reduces plant water use by soybean due to decreased stomatal conductance and transpiration (Allen and Boote 2000; Booker et al. 2004; Bernacchi et al. 2007). Net photosynthesis in soybean is increased by 23–39% at twice-ambient CO_2 (Allen and Boote 2000; Ainsworth et al. 2002). A decline in photosynthesis occurs in some plants grown at elevated CO_2 (acclimation), accompanied by a decrease in Rubisco and nitrogen concentration. This does not occur in soybean, probably because nitrogen supply keeps up with increased carbon assimilation via stimulated nitrogen fixation (Allen and Boote 2000). Photosynthetic and production WUE were both increased by elevated CO_2 (Allen et al. 1994; Allen and Boote 2000; Booker et al. 2004). Gene expression studies with soybean treated with elevated CO_2 revealed increased transcription of genes involved in carbohydrate metabolism, which was suggested to provide increased energy and biochemical precursors for leaf expansion and growth (Ainsworth et al. 2006).

Increasing CO_2 from a concentrations of 330–660 ppm increased soybean seed yield by about 32% on average based on data from a large number and variety of experiments (Allen and Boote 2000). Soybean yield was increased by 17% with a CO_2 increase from 380 to 550 ppm in a free-air experiment (Long et al. 2005). Crop model projections for soybean production in Argentina based on GCM GISS modeled climate conditions for 2050 with an atmospheric CO_2 concentration of 550 ppm indicated an increase of 20–30% compared with 1971–94 (Magrin et al. 1997). Higher temperatures and CO_2 concentration enhanced grain production, particularly in the cooler southern region. For the Southeastern United States, a crop model coupled with climate scenarios projected a 6–14% increase in soybean yields with warming, irrigation and elevated CO_2, with the negative influence of 2 °C higher temperature counteracted by a CO_2 increase from 330–550 ppm (Alexandrov and Hoogenboom 2000). Simulations of soybean yields in Georgia, USA, showed increases with elevated CO_2 under both irrigated and rainfed conditions. Nationally, soybean yields are projected to increase by about 10% with a mean temperature increase of 1 °C and CO_2 at 560 ppm compared with 365 ppm, but yields decline by 5–10% with a temperature increase of 2.5 °C (Thomson et al. 2005).

Limitations to the projections included uncertainty in climate predictions of temperature and precipitation, changes in the frequency of extreme weather events and frequency of drought, management adaptation and technological improvements, and indirect impact of weeds, diseases, and insect pests due to climate changes (Alexandrov and Hoogenboom 2000; Thomson et al. 2005), such that these projections should be considered, at most, a subset of the range of possible climatic conditions in the coming decades. Variability in projected soybean yields was most strongly affected by variation in precipitation projected by the climate models (Thomson et al. 2005).

In some legumes, such as soybean and peanut, elevated CO_2 enhances symbiotic nitrogen fixation (Serraj and Sinclair 2003; Rogers et al. 2006; Tu et al. 2009). This is likely related to increased availability of photosynthate from increased photosynthesis that stimulates growth and demand for nitrogen along with increased carbon allocation below ground (Rogers et al. 2006). Rogers et al. (Rogers et al. 2006) found that CO_2 enrichment ameliorated the early season decline in plant nitrogen concentration in soybean, indicating improved nitrogen assimilation and probably nitrogen fixation during reproductive growth. Small differences in plant nitrogen concentration at harvest and decreased $\delta^{15}N$ values showed that elevated CO_2 enhanced nitrogen acquisition from the soil and through symbiotic nitrogen fixation in peanut (Tu et al. 2009).

There are findings from open-top chamber and free-air systems that soil organic matter (SOM) turnover appears to be accelerated under elevated CO_2 (Peralta and Wander 2008; Moran and Jastrow 2010; Cheng et al. 2011). In a 6-year no-till soybean–wheat study, soil microbial activity, biomass, community composition, and nitrogen mineralization were increased by elevated CO_2 (Cheng et al. 2011). Accelerated SOM turnover rates may have long-term implications for soils productive and C storage potential and calls for deeper investigation into C and N dynamics in highly productive row crop systems.

2.02.6 Tropospheric Ozone

Ozone is formed in the lower atmosphere (troposphere) when its precursors (nitrogen oxides and carbon monoxide) generated mainly from fossil fuel combustion react with volatile organic compounds and oxygen in the presence of sunlight. Natural vegetation is also a source of volatile organic compounds and has significant influences on regional atmospheric chemistry. Ozone is a greenhouse gas. It contributes the third largest increase in direct radiative forcing (~12%) and first after the long-lived species (Prather et al. 2001). It also modifies the lifetimes of other greenhouse gases such as methane through its reactions with OH. Activities in the energy-generating and transportation sectors generate the majority of ozone precursors although off-road vehicles, methane emissions, large fires, and industrial processes contribute to surface-level ozone as well. Current global tropospheric ozone concentration is about 34 DU, although its budget is difficult to derive owing to its high chemical reactivity and rapid turnover (Prather et al. 2001). Mean surface ozone ranges from 40 to 50 ppb over large parts of North America, southern Europe, and Asia (Dentener et al. 2006). Ozone is not limited to urban areas. Ozone and its precursors can be transported hundreds of kilometers into rural areas where agricultural activities occur and native and managed forests exist, including culturally important Class I Wilderness Areas. Efforts to reduce pollution emissions have mostly succeeded in lowering peak concentrations, but mean ozone levels in many areas remain high enough to impact crops and forests (Booker et al. 2009).

There is concern that future reductions in local ozone formation, due to stricter air quality standards, will be offset by rising background levels as global industrialization increases. There is evidence that ozone, along with it precursors, is increasingly transported from Asia over the Pacific Ocean to North America. Models (A1FI and A2 IPCC SRES scenarios) project increasing ozone precursor emissions (mainly NO_x and CH_4) and predict tropospheric ozone concentrations of 44 DU and 55 DU by 2050 and 2100, respectively (Prather et al. 2001, 2003). More immediately, by 2030, 'business as usual' SRES scenarios project near-surface ozone increases that range from 9 to 34% (averaging 25%), about 5 (+2 to +7) ppb over the Northern Hemisphere, which would seriously impede ambient air quality standard attainment (Prather et al. 2003). If proposed emission control legislation is implemented worldwide, however, ozone concentrations in 2030 could be stabilized at 2000 levels except in regions (e.g., India, China) with large increases in energy, transportation, and industrial activities (Dentener et al. 2006). Efforts to mitigate climate change are also projected to lower ground-level ozone concentrations and radiative forcing (West et al. 2007). However, climate models suggest that air pollution episodes will occur more frequently during the growing season in regions such as the Midwestern and Northeastern United States due to increases in temperature and changes in atmospheric circulation patterns (Mickley et al. 2004; Dentener et al. 2006).

Many well-executed and reproducible studies indicate that soybean growth and yield are suppressed by ambient ozone levels now occurring in many regions of the United States and worldwide (Morgan et al. 2003; Booker et al. 2009; Cho et al. 2011). Independent verification of soybean yield losses at current ambient ozone concentrations in the Midwestern United States was accomplished using ground and satellite ozone measurements (**Figure 2**) (Fishman et al. 2010). Yield losses on the order of 10% could be estimated through the use of a multiple linear regression model (Fishman et al. 2010). Yield loss trends were consistent with results obtained from open-top chamber experiments and from the open-air exposure experiment conducted in the Midwest (SoyFACE).

Recent advances in understanding plant responses to ozone derive from innovative genomic and proteomic studies (Cho et al. 2011). Following uptake through the stomata in the leaf, ozone interacts with cellular processes to cause inhibition of photosynthesis, growth, and yield. Gene expression and proteomic studies show that detrimental ozone effects are likely caused by a combination of chemical toxicity and plant-mediated responses that either amplify or contain injury.

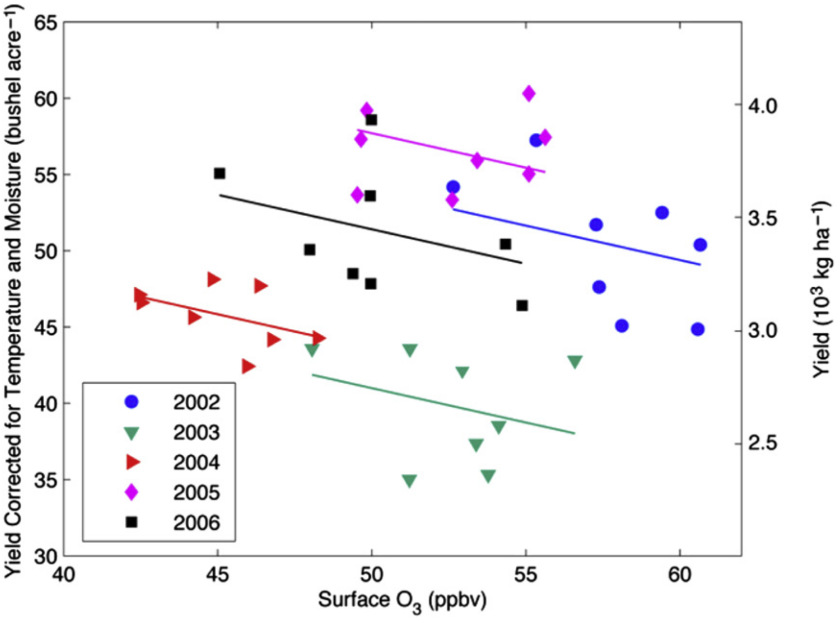

Figure 2 The relationship between soybean seed yield and surface ozone over the southern region of Illinois and Indiana, USA (37–40 °N) from 2002 to 2006 (Fishman et al. 2010). Yield data were obtained from the USDA National Agricultural Statistical Service and summer ozone data were obtained from U.S. Environmental Protection Agency monitoring stations. All data were provided and compiled on a county-wide basis. An investigation of widespread ozone damage to the soybean crop in the upper Midwest determined from ground-based and satellite measurements. Atmospheric Environment 44:2248–2256.

Expression of genes and proteins involved in photosynthesis is suppressed while carbohydrate catabolism, oxidative signaling, and antioxidant and defense pathways are stimulated by ozone (Ahsan et al. 2010; Cho et al. 2011). The responses are hypothesized, due in part to a need for energy and reducing power to detoxify and repair damage caused by oxidative molecules (Ahsan et al. 2010). Similarities between responses to ozone and programmed responses to biotic pathogens have led to conceptual breakthroughs in understanding ozone impacts (Sandermann Jr. et al. 1998).

At the agroecosystem level, ozone effects on soil carbon and nitrogen dynamics have not been well characterized. Changes in below ground processes are hypothesized to result mainly from ozone effects on plant carbon allocation and biomass production, which are generally reduced by ozone, especially in roots (Andersen 2003). In a 6-year no-till soybean–wheat study conducted in open-top field chambers, there was no effect of ozone on soil microbial activity, biomass, community composition, or nitrogen mineralization, in contrast to elevated CO_2, which increased these processes (Cheng et al. 2011). Plant residue input in the open-top chamber experiment was less in the added ozone treatment, but no effect on soil nitrogen was found (Cheng et al. 2011). In a study at SoyFACE with 20% higher ozone, bulk soil nitrogen and carbon concentrations were 12 and 15% higher, respectively, than in soil from plots exposed to ambient air (Pujol Pereira et al. 2011). It was suggested that decomposition processes may have been slower under elevated ozone due to the lower amount of plant material input. Decreased N_2 fixation with elevated ozone has been observed in soybean, possibly related to decreased carbon availability due to inhibition of photosynthesis (Flagler et al. 1987; Pausch et al. 1996).

There is no evidence that soil carbon and nitrogen dynamics in highly managed agroecosystems are significantly influenced by ambient ozone in the United States, although it is possible that substantial reductions in biomass production due to higher future ozone levels could influence soil nutrient cycling processes. It should be noted, however, that the potential influence of high ambient ozone levels on soil nutrient cycling has not been widely evaluated.

Ozone sensitivity varies widely among soybean cultivars (Heagle 1989; Burkey and Carter 2009; Betzelberger et al. 2010), and breeders may have inadvertently selected for ozone resistance. Crop breeding programs regularly produce higher yielding varieties that, along with improved management and production practices, increase yields. Selection for ozone tolerance may be occurring as a consequence of yield trials in the field, but ozone tolerance is neither evaluated nor selected in current breeding programs. Genetic approaches could be employed to develop new varieties with improved ozone tolerance.

Ozone toxicity in plants is not wholly dependent on ambient ozone concentration. Other factors influence plant responses to ozone, such as vapor pressure deficit, temperature, soil water content, $[CO_2]$, diurnal and developmental stomatal conductance behavior, plant phenology, and differential cultivar sensitivities to ozone. There is good evidence, for example, that ambient ozone concentration and air temperature are positively correlated. Further research on how climate conditions affect plant responses to ozone is needed.

2.02.7 Climate Factor Interactions and Yield

Analyses of historical temperature–yield relationships suggest that warming would offset some of the yield gains from technological advances, rising CO_2, and other non-climatic factors (Lobell and Field 2007). Increases in atmospheric CO_2 also tend to ameliorate ozone injury in a number of crops, including soybean (Figure 3) (Ainsworth and Long 2005; Booker and Fiscus 2005; Fiscus et al. 2005; Booker et al. 2009). The converse is also true – ozone offsets elevated CO_2 aerial fertilization effects, depending on the cultivar. Elevated CO_2 and ozone pollution interact to affect crop yields, suggesting that projected benefits of rising CO_2 in the atmosphere are overly optimistic and are based on conceptual models that are too simplistic. It is likely that elevated CO_2 would reduce detrimental effects of ozone on soybean yields, although the interaction becomes less effective as ozone concentrations increase. It is unknown how combinations of elevated CO_2, ozone, and warming would affect soybean yields. Elevated CO_2 will reduce ozone uptake and transpiration, and increases not only WUE and TE, but also the canopy temperature, in addition to the effect of higher air

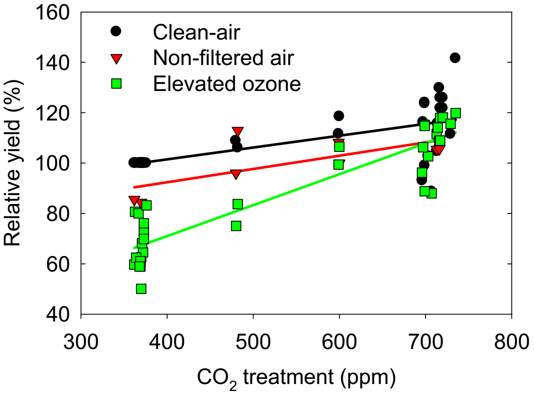

Figure 3 The effects of elevated CO_2 and ozone on relative seed yield of Essex soybean. Plants were treated with a range of CO_2 concentrations in combination with clean-air (charcoal-filtered air), non-filtered air, or elevated ozone in open-top field chambers. Seed yields were expressed relative to yields in the ambient CO_2/clean-air treatments (control). Seasonal ozone concentrations in the clean-air, non-filtered air and added ozone treatments averaged 23, 46 and 74 ppb (12 h average). Data were obtained from 17 experiments conducted over 11 years at Raleigh, NC, USA (Fiscus, E. L., C. D. Reid, J. E. Miller, and A. S. Heagle, 1997: Elevated CO_2 reduces O_3 flux and O_3-induced yield losses in soybeans: possible implications for elevated CO_2 studies. *J. Exp. Bot.*, **48**, 307–313; Heagle, A. S., J. E. Miller, and W. A. Pursley, 1998: Influence of ozone stress on soybean response to carbon dioxide enrichment. III. Yield and seed quality. *Crop Sci.*, **38**, 128–134; Booker, F. L., E. L. Fiscus, and J. E. Miller, 2004: Combined effects of elevated atmospheric carbon dioxide and ozone on soybean whole-plant water use. *Environ. Manag.*, **33**, S355–S362; Booker, F. L., and E. L. Fiscus, 2005: The role of ozone flux and antioxidants in the suppression of ozone injury by elevated CO_2 in soybean. *J. Exp. Bot.*, **56**, 2139–2151; Booker, F. L., J. E. Miller, E. L. Fiscus, W. A. Pursley, and L. A. Stefanski, 2005: Comparative responses of container- versus ground-grown soybean to elevated CO_2 and O_3. *Crop Sci.*, **45**, 883–895; Fiscus, E. L., F. L. Booker, J.-J. B. Dubois, T. W. Rufty, J. W. Burton, and W. A. Pursley, 2007: Carbon dioxide enhancement effects in container- versus ground-grown soybean at equal planting densities. *Crop Sci.*, **47**, 2486–2494).

temperature and possibly vapor pressure deficit. This will tend to increase transpiration, respiration, and other physiological processes, including developmental rate. Both elevated CO_2 and water stress increased leaf temperatures and leaf-to-air vapor deficit of soybean (Allen et al. 1994).

Land-use changes associated with soybean production are generally correlated with changes in precipitation (Thomson et al. 2005). In Brazil, there is concern that deforestation is indirectly related to increasing soybean cultivation as agriculture encroaches on pastures, displacing them to the frontier and encouraging deforestation (Barona et al. 2010; Arima et al. 2011).

2.02.8 Conclusion

Drought is the primary climate change threat to crops, while increasing temperature is secondary (Dai 2011; Sinclair 2011). There has been substantial progress in interpreting the effects of water stress, elevated CO_2 and ozone on plants, and the mechanisms by which those effects are mediated. However, there is much to be done in a practical sense before that information can be translated into useful products. A current need is to identify genetic sources of adaptive traits that breeders can use to improve soybean. New crop cultivars, many of which are genetically modified, are being placed into production without specific consideration of their sensitivity to rising CO_2 or air pollution. Crop breeding programs need to incorporate a selection of traits for improved plant tolerance to abiotic stress in order to maintain and increase crop yields and nutritive quality. With rising CO_2 and temperatures, soybean yields would likely increase, but become more variable year to year (Sinclair and Rawlins 1993). However, with drought, soybean yield would decline strongly, which leads to supply and price volatility, which is a significant risk to the marketplace (Sinclair and Rawlins 1993).

Application of genomics has potential to improve stress tolerance in soybean. Screening modern cultivars and/or germplasm used in current breeding programs is the current state of the science, but will be limited to optimizing for tolerance within a fairly narrow portion of the genetic base. Greater long-term impact may be derived from initially screening a broader set of germplasm to identify genotypes with greater or more diverse sources of tolerance to various abiotic stresses such as drought or ozone (Carter et al. 2004; Burkey and Carter 2009). Breeding for ozone tolerance, for example, may enhance plant tolerance to other abiotic stresses, or vice versa, so it may be useful to screen for ozone tolerance within germplasm that is developed to withstand other stress factors, and the converse may be true as well (Burkey and Carter 2009).

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2.03 Climate Impact Analysis and Adaptations for Sustainable Rice Production System

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2.03.1 Introduction

Food security is a critical issue in the developing world. For about three billion people, more than half the world's population, rice is staple food. In Asia as a whole, much of the population consumes rice in every meal. In many countries, rice accounts for more than 70% of human caloric intake. Rice is rich in nutrients and contains a number of vitamins and minerals. It is an excellent source of complex carbohydrates, the best source of energy. Rice is a member of the grass family (Gramineae) and belongs to the genus *Oryza* under tribe Oryzeae. The wild species are widely distributed in the humid tropics and subtropics of Africa, Asia, Central and South America, and Australia (Chang 1985). Of the two cultivated species, African rice (*Oryza glaberrima* Steud.) is confined to West Africa, whereas common or Asian rice (*Oryza sativa* L.) is now commercially grown in 112 countries, covering all continents. India is the second largest producer of rice in the world after China with total production of 143 million tonnes (**Figure 1**) accounting for 21% of total rice production (FAO2010). Rice in India is grown on 43 million ha in a diverse set of agro-environments varying in seasons, temperatures, rainfall, soil types, hydrology, varieties, and input management. It is the staple food for a large majority of population and constitutes 43% of the total food (cereal and pulse grain) production. The nutritional composition of rice is given in **Table 1.**

In recent years, with the growing recognition of the possibility of changes to regional and local temperatures and precipitation, an increasing emphasis on world food security, in general, and its regional impacts, in particular, has come to the forefront of the scientific community. There is now clear evidence for an observed increase in global annual average temperatures. The total greenhouse gas (GHG) emissions due to anthropogenic activities have grown substantially with an increase of 70% between 1970 and 2004. Out of all the GHGs, carbon dioxide (CO_2) is the most important greenhouse gas which recorded 80% increase from 21 to 38 (Gt) between 1970 and 2004 which constitutes 77% of total CHG emissions in 2004. Similarly, the growth rate of CO_2-eq emissions was much

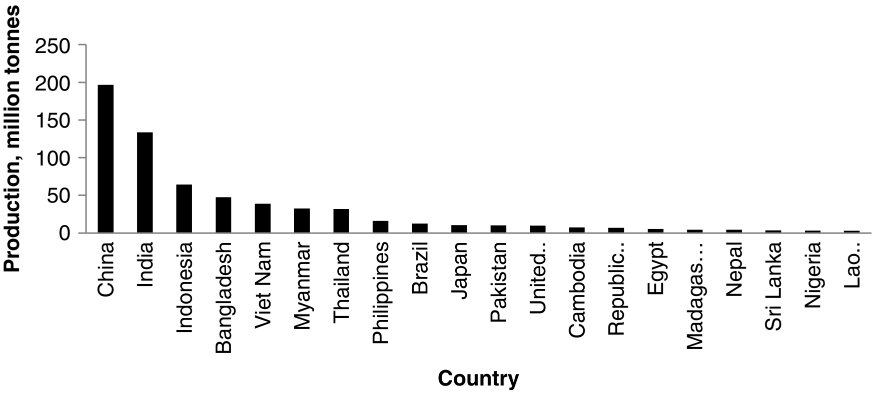

Figure 1 Rice production in the world for the year 2010. Source: Made by author (data from FAOSTAT)

Table 1 Nutritional value of rice

Nutrient	*Amount in 100 g (Percentages are relative to US recommendations for adults)*
Energy	1527 k J
Carbohydrates	79.95 g
Sugars	0.12 g
Dietary fiber	1.3 g
Fat	0.66 g
Protein	7.13 g
Thiamin	0.07 mg (5%)
Riboflavin	0.05 mg (3%)
Niacin	1.6 mg (11%)
Pantothenic acid	1.01 mg (20%)
Vitamin B6	0.16 mg (13%)
Calcium	28 mg (3%)
Iron	0.8 mg (6%)
Magnesium	25 mg (7%)
Phosphorus	115 mg (16%)
Potassium	115 mg (2%)
Zinc	1.09 mg (11%)
Manganese	1.09 mg

Source: http://en.wikipedia.org/wiki/Rice

higher between 1995 and 2004 (0.92 Gt CO_2-eq/year) than during 1970–94 (0.43 Gt CO_2-eq/year). India faces major challenges to increase its food production to the tune of 300 million tons in order to feed its ever growing population, which is likely to reach 1.30 billion by the year 2020 (Figure 2). To meet the demand for food from this increased population, the country's farmers need to produce 50% more grain by 2020 (Paroda and Kumar 2000). The problem has became acute because urbanization and industrialization have rapidly dwindled the per capita availability of arable land from 0.48 ha in 1950 to 0.15 ha by 2000 and is likely to further reduce to 0.08 ha by 2020 (FAO, 2010). Crop growth, development, water use, and yield under normal conditions are largely determined by weather during the growing season. Even with minor deviations from the average weather patterns, the efficiency of precisely applied inputs and food production is seriously impaired. It is, therefore, important to quantify the possible impact of climate change on rice yields.

2.03.2 Constraints in Rice Production

Rice is grown in irrigated as well as rainfed ecosystem posing several limitations to the yield. The productivity of rainfed ecosystem is significantly lower than the irrigated ecosystem, because of irregularity in rainfall in both amount and distribution during the crop growing period. The current climate is causing an increasing high intensity rainfall and long dry spell, which is a serious threat to rice production as it requires sufficient water throughout its growing period. Though the rice productivity of irrigated ecosystem is higher than the rainfed, there exist large gaps between actual farmers' yield and potential yield (Table 2). For minimizing the yield gap, it requires the concerted efforts, from governments' rice policies to ensuring appropriate land leveling, efficient water control, appropriate inputs (improved seeds, fertilizers, pesticides) supplies, credit provision, and effective institutional supports (research, extension, marketing, incentive rice price). The major constraints of rice production system are discussed as follows.

Table 2 Yield gaps of irrigated rice in selected countries, FAO 2004

Country	*Actual farm yield (tonnes/ha)*	*Potential farm yield (tonnes/ha)*	*Yield Gap (tonnes/ha)*
India (northern zone)	4.0	6.8	2.8
Korea, Republic of	7.0	7.6	0.6
Philippines	5.5	7.5	2.0
Viet nam	6.5	8.5	2.0
Egypt	8.5	10.4	2.1
Madagascar	4.1	6.0	2.1
Italy	6.0	9.0	3.0
Brazil	5.5	8.5	3.0

Source: http://www.unis.unvienna.org/documents/unis/calendar/year_of_rice/factsheet5.pdf

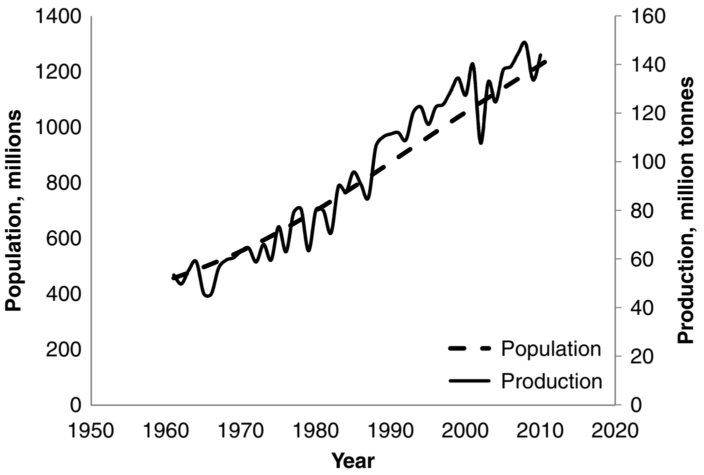

Figure 2 Rice production and population growth of India (1961–2009). Source: Made by author (Data from FAOSTST)

2.03.2.1 Abiotic Stress

Crop growth, development, and yield are dependent on weather parameters in season. Any minor deviations in the weather parameters can hamper the growth and development leading to reduction in the yield. Climate impacts on rainfall and runoff affect the availability of water for irrigation in many regions and countries in the world. A decline in rainfall along with an increase in temperature, for example, would increase crop water requirements, due to high evapotranspiration, while less rainfall would increase crop net irrigation water requirements. As a result, the already existing water scarcity problem would be exacerbated in many regions and countries, and affect food production.

Rice plant growth can be divided into three agronomic stages of development:

1. Vegetative (germination to panicle initiation): This phase involves tillering, increase in plant growth parameters, and leaf emergence.
2. Reproductive (panicle initiation to heading): This stage is characterized by panicle initiation, flag leaf, heading, and flowering.
3. Grain filling and ripening or maturation.

Light intensity and temperature are very important during this interval since 60% or more of the carbohydrates used in grain filling are photosynthesized during this time interval. All stages of development are sensitive to temperature. It is the main factor controlling the rate of crop development (Table 3). Development generally accelerates as temperature increases which is linearly correlated up to critical temperature. In experiments under controlled conditions from 25 to 35 °C, mean grain weight declined 16% for each 5 °C increase in temperature (Asana and Williams 1965). For every 1 °C rise in temperature, there is a depression in grain yield by 8–10%, mediated through 5–6% fewer grains and 3–4% smaller grain weight.

2.03.2.1.1 Impact of Elevated CO_2 and Temperature

The different rice varieties have different period of growth cycles. *O. glaberrima* has the ability to anthese during early morning and escape high temperatures during the later hours of the day (Yoshida 1981; Prasad et al. 2006). On the other hand, *O. sativa* spp. flower later during the day (Prasad et al. 2006) experiencing high day temperatures, which may lead to the spikelet sterility. The early morning flowering advantage of *O. glaberrima* has been exploited in interspecific crosses between *O. glaberrima* and *O. sativa* to advance peak flowering toward early hours.

High temperatures (35 °C) during anthesis and microsporogenesis resulted in 71 and 34% decline in the spikelet fertility, respectively (Yoshida 1981). Several long- and short-term CO_2 enrichment studies revealed that doubling the current ambient CO_2 increased leaf photosynthetic rate by 30–70% (Ghilidyal and Natu 2000). The magnitude of this increase depends on rice cultivar, growth stage, and environment. Since one of the major effects of elevated CO_2 on net photosynthesis is suppression of photorespiration, it could be expected that optimum temperature for photosynthesis could shift upwards. The effect of CO_2 enrichment on rice leaf area development is small (Nakagawa et al. 1993; Kim et al. 1996; Ziska et al. 1997), but the canopy photosynthetic response is mainly attributed to responses at the unit leaf area level. Mathauda et al. (2000) showed the effect of temperature increase on rice crops. An increase of temperature decreases the life span, grain yield, maximum leaf area index, biomass, and straw of the rice. Elevated CO_2 increases phenological developmental rate and hence reduces the number of days to heading (Baker et al. 1990; Nakagawa et al. 1993; Kim et al. 1996). Baker et al. (1990) found that elevated CO_2 did not significantly affect the interval between similar growth stages of successive leaves of rice, but the leaf number was reduced due to accelerated phenological development. Factors that have been known to influence the response of rice plant growth to elevated CO_2 include phenological stage, cultivar, season, air temperature, and nutrient supply. However, our understanding of these factors still cannot satisfactorily explain the large variations of results obtained in different high CO_2 studies. The reported yield reductions, under increased night temperature cannot be fully explained by effects on respiration. Other mechanisms also may contribute to the observed yield reduction, such as differential effects of night versus day temperature on tillering, leaf area expansion, stem elongation, grain filling, and crop phenological development. Greater fundamental understanding is needed regarding the effects of night temperature on physiological processes governing crop growth and yield development (Peng et al. 2004).

Lobell (2007) conducted a study to evaluate the changes in the diurnal temperature range, which affect crop yield. Data on national crop yields for 1961–2002 in the 10 leading producers of wheat, rice, and maize were combined with datasets on climate and crop locations to evaluate the empirical

Table 3 Response of phasic development to temperature, photoperiod and vernalization

Sl. no	*Developmental phase*	*Temperature*	*Photoperiod*	*Vernalization*
1	Sowing-emergence	++++/+++++	0	0
2	Emergence-double ridges	+++/+++++	0/+++	0/+++++
3	Double ridges-terminal spikelet	+/+++	0/+++++	0/+++++
4	Terminal spikelet-heading	+++/+++++	0/+++	0/+(?)
5	Heading-anthesis	+++/+++++	0/+(?)	0
6	Anthesis-maturity	+++/+++++	0	0

+++++: strong; +++: moderate; +: slight; 0: doesn't affect; ?: uncertainty.
Source: http://www.fao.org/docrep/w5183e/w5183e08.htm

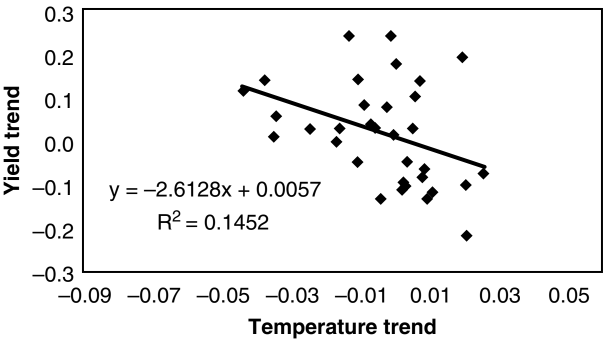

Figure 3 Temperature and yield trend over major rice growing sites in India

relationships between average temperatures (T_{avg}), diurnal temperature range (DTR), and crop yields. In several rice and maize growing regions, including the two major nations for each crop, there was a clear negative response of yields to increased DTR. This finding reflects a nonlinear response of yields to temperature, which likely results from greater water and heat stress during hot days. In many other cases, the effects of DTR were not statistically significant, in part because of the correlations of DTR with other climate variables, and the relatively short length of the time series resulting in wide confidence intervals for the estimates.

To evaluate whether a subset of future plausible changes in DTR are relevant to crop impact assessments, yield responses to projected changes in T_{avg} and DTR by the year 2046–65 from 11 climate models were estimated. The mean of climate model projections was increased in DTR in most seasons and locations where wheat is grown, mixed projections for maize, and a general decrease in DTR for rice. The estimated impacts of DTR changes on yields were generally small (<5% change in yields) relative to the consistently negative impact of warming of T_{avg}. However, DTR changes did significantly affect yield responses in several cases, such as in reducing US maize yields and increasing India rice yields. Because DTR projections tend to be positively correlated with T_{avg}, estimates of yield changes for extreme warming were particularly affected by including DTR (up to 10%). In India also, an increasing trend of daily average temperature resulted a decreasing trend in rice grain yield as estimated using past years weather data (Figure 3).

Many of these impact studies were aimed at assessing crop development shifts and yield variations under changes in climate conditions. These analyses showed that increasing temperatures generally shortened the growing period of commercial crops (e.g., Bindi et al. 1996), resulting in a shorter time for biomass accumulation. On the other hand, changes in yields were not homogeneous and dependent on crop phenology (e.g., summer and winter crops), crop type (e.g., C3 and C4 plants), or environmental conditions (water and nutrient availability) (Ainsworth and Long 2005). Crop modeling approaches are being used to evaluate the effect of elevated CO_2 and temperature on change in yield under projected climate change scenarios. Results of similar study conducted by Matthews et al. (1997) in Asian countries are given in Table 4.

Table 4 Mean predicted changes (%) in potential yields under the 'fixed' temperature and CO_2 scenarios using ORYZA1 and SIMRIW crop models.

	Temperature increments			
	+0 °C	*+1 °C*	*+2 °C*	*+4 °C*
ORYZA1				
340 ppm	0.0	−7.3	−14.2	−31.0
$1.5 \times CO_2$	23.3	14.3	5.6	−15.7
$2 \times CO_2$	36.4	26.4	16.8	−7.0
SIMRIW				
340 ppm	0.0	−4.6	−9.8	−26.2
1.5 × ppm	13.0	7.8	1.9	−16.6
2 ppm	23.9	18.2	11.7	−8.5

Matthews, R . B ., M. J. Kropff, T. Horie, and D. Bachelet, 1997: Simulating the impact of climate change on rice production in Asia and evaluating options for adaptation. *Agric. Syst.*, **54,** (3), 399–425.

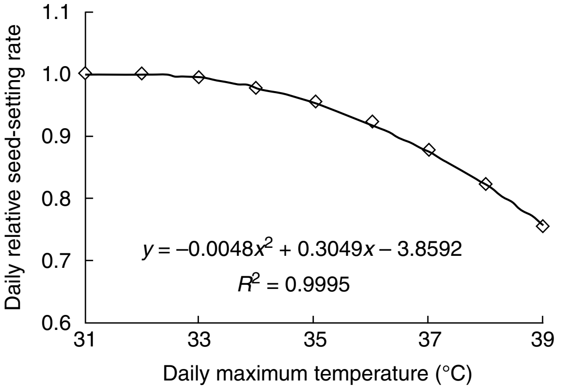

Figure 4 Relationship between daily maximum temperature and relative seed-setting rate under natural change pattern of temperature (Chun-Lin, S. H. I., J. I. N. Zhi-Qing, J.-C. Zheng, and R.-S. Tang, 2008: Effect of high temperature at meiosis stage on seed-setting rateinrice, *Acta Agron. Sin*, **34** (4), 627–631.)

Heading and meiotic stages are the most important stages of rice crop and both these stages are very sensitive to temperature. Temperature above 35 °C at the above two growth stages is very harmful for grain development of rice crop. High temperature results in spikelet sterility, which further results in relative seed-setting rate and grain yield (Sataka and Yoshida 1978; Matsui et al. 2001; Prasad et al. 2006). Chun-Lin et al. (2008) evaluated the effect of high temperature on rice yield quantitatively by conducting experiments on two rice cultivars. They conducted the experiment with a controlled (natural) temperature and with 31, 33, 35, 37, 39, and 41 °C at different meiotic stages of rice. Effect on the seed-setting rates was observed on both cultivars when the temperature was lower than 33 °C. But the temperature and its duration had a negative impact on seed-setting rate and the decrease rate follows a quadratic equation (Figure 4).

Unique field experiments indicated that the effects of elevated CO_2 and temperature on rice plants could increase methane emissions from rice fields, providing an important feedback to climate change from rice cultivation (Olszyk et al. 1999; Ziska et al. 1997). Methane gas emission from

Table 5 Methane gas emission from rice fields in selected countries

Country	*Total amount of emitted CH_4 (Gg CH_4)*	*Contribution of rice methane to total methane emission (%)*	*Contribution of rice methane to total greenhouse gas emission (%)*
USA in 2005	328	1.3	0.1
Italy in 2005	70	3.7	0.3
Japan in 2004	274	24.0	0.4
China in 1994	10 182	30.0	5.9
India in 2006	6600	35.0	9.8

Source: Leip, A. and S. Bocchi, 2007: Contribution of rice production to greenhouse gas emission in Europe. *Proceedings of the 4th Temperate Rice Conference, 25–28 June 2007, Novara, Italy*, 32–33.

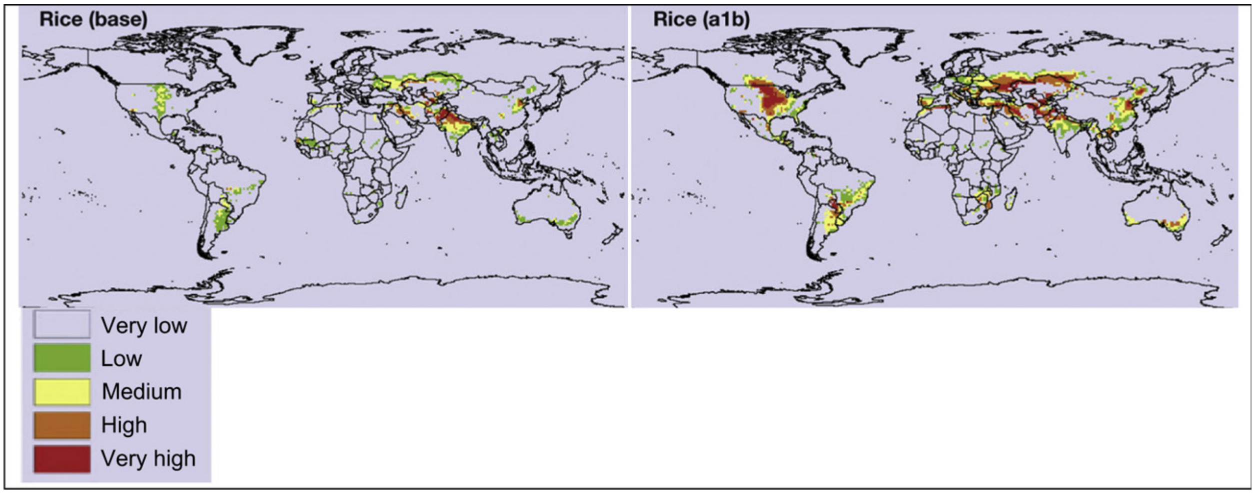

Figure 5 The maximum heat stress intensity within a 30-year simulation in areas suitable for the production of rain-fed wetland rice for the baseline climate (Base, 1971–2000) and the A1B climate change scenario (2071–2100). (Teixeira, E. I., et al., Global hot-spots of heat stress on agricultural crops due to climate change. Agric. Forest Meteorol. (2011), doi:10.1016/j.agrformet.2011.09.002 (article in press).)

rice fields in different countries is given in Table 5 (Leip and Bocchi, 2007). Elevated CO_2 or in combination with elevated temperature produced a large increase in methane emissions from rice fields compared to current conditions; primarily due to a large increase in below ground biomass. In contrast, elevated temperature alone tended to decrease methane emissions from rice fields. The magnitude of these changes in methane emissions from rice fields were not predicted by current plant growth simulation models (Olszyk et al. 1999).

Global hot spots of crop heat stress overlap with major agricultural regions such as Eastern China, the Northern United States, Southwestern Russian Federation, and Southern Canada in one plausible Intergovernmental Panel on Climate Change (IPCC) scenario (Figure 5). This indicates that agricultural production in temperate countries likely suffers from substantial production losses from climate extending the findings of previous studies that impacts would mainly occur in subtropical and tropical regions (IPCC 2007a; Fischer et al. 2002, 2005).

It is predicted that CO_2 concentration will reach twice the present level in the next century (Houghton et al. 1990). Rising CO_2 concentrations can stimulate photosynthesis and growth of a wide range of C3 plants. The microclimate, nutrient conditions, and limited usable area in the chambers can change the plant responses to elevated CO_2. The predictions obtained from laboratory experiments should be evaluated under field conditions. In addition to the ecophysiological processes of plants examined in the laboratory experiments, elevated CO_2 could change various environmental conditions, including the carbon cycle and nitrogen metabolism. Increasing carbon input to the soil through increased root growth, root exudation, altered litter quality, and increased soil water use under elevated CO_2 can all affect soil nitrogen transformations and carbon dynamics. Along with CO_2 another important factor is O_3. Ground level O_3 concentrations have been increasing worldwide (and are expected to continue to increase) due to increased emissions of pollutants that react to produce O_3 (Vingarzan 2004). High atmospheric concentrations of ozone can cause damage to leaves and decreased plant growth and photosynthesis (Feng et al. 2008; Morgan et al. 2003). The primary location of O_3 injury to plants is the internal tissues of leaves. Decreased openness of stomata under elevated CO_2 can therefore decrease exposure of sensitive tissues to ozone. Elevated CO_2 substantially decreases the negative effects of high ozone on photosynthesis, growth, and seed yield in both soybeans and rice. There is little information concerning the respiratory behavior of the rice crop throughout its growth cycle. Carbon losses due to growth and maintenance

Table 6 Number of grains per m^2 (NOG), percentage of filled grains (PFG), individual grain weight (GRW), seed yield (Y), and harvest index (HI) of rice grown under elevated (ca 570 μmol mol^{-1}) and ambient CO_2 (ca 370 μmol mol^{-1}) open top chambers and in open field conditions in Maha (Jan–Mar) and Yala (May–Aug) seasons of 2001

Treatment	*NOG (m^{-2})*	*PFG (%)*	*GRW (mg)*	*Y (g m^{-2})*	*HI*
Maha					
Elevated CO_2	47 007	82.9	24.9	71	0.47
Ambient CO_2	42 336	76.0	24.5	783	0.45
Open	41 793	72.1	24.0	723	0.41
$LSD_{0.05}$	2345	4.2	1.3	95	0.06
Yala					
Elevated CO_2	39 862	84.2	23.9	838	0.52
Ambient CO_2	29 391	81.7	25.0	604	0.51
Open	26 760	88.4	24.7	587	0.50
$LSD_{0.05}$	3005	2.3	1.9	62	0.04

$LSD_{0.05}$ Least significant difference at $p = 0.05$. Adapted from De Costa, W. A. J. M., W. M. W. Weerakoon, H. M. L. K. Herath, K. S. P. Amaratunga, and R. M. I. Abeywardena, 2006: Physiology of yield determination of rice under elevated carbon dioxide at high temperatures in a subhumid tropical climate. *Field Crops Res.*, **96,** 336–347.

respiration typically amount to 40–60% of the total carbon fixed by a crop (Pritchard and Amthor 2005). In tropical areas, this percentage may even be higher. Early in the growing season, growth respiration dominates. At later stages, maintenance respiration may account for 50% of the total respiration loss and it is much affected by environmental conditions within the crop canopy. Since growth respiration is proportional to crop biomass, it can only be reduced by lowering the growth rate or by changing the biochemical composition of the phytomass produced. In contrast, maintenance respiration can be altered through genetic improvement and management. Some evidence of genetic variation in maintenance respiration exists for other crops (Winzeler et al. 1988; Earl and Tollenaar 1998) and there have also been attempts to select more respiration efficient germplasm (Wilson and Jones 1982).

Rice yield was found to be increased with increase in CO_2 concentration (Baker et al. 1990) from experiments conducted by the International Rice Research Institute (IRRI). The experiment conducted by Baker et al. revealed that 28 °C is the optimum temperature for rice growth. At the optimum temperature level, the increase in CO_2 concentration increased the grain yield through an increase in the number of filled grains per panicle and an increase in individual seed mass of about 1–2 mg per seed. Along with that, the CO_2 enrichment also increased above ground biomass and harvest index at the optimum temperature level.

An experiment was conducted on rice growth with elevated CO_2 concentration. Rice was grown over two seasons in a subhumid tropical climate in Sri Lanka, at elevated CO_2 concentration, and ambient CO_2 in open top chambers with open field plots to estimate chamber effects. The CO_2 within the chambers was maintained around target concentration by a computer-based real time data acquisition and control system. Rice under elevated CO_2 showed significantly greater (20 and 11% in the two seasons) RUE relative to the ambient CO_2. The radiation use efficiency under elevated CO_2 did not show a reduction during the post-heading period. Consequently, the total biomass at harvest was 23–37% greater under elevated CO_2. Observations were that the number of grains initiated and percentage of grains filled were significantly greater under elevated CO_2, resulting in final seed yields being 24 and 39% greater than ambient as shown in Table 6 (De Costa et al. 2006).

Yang et al. (2009) using free air CO_2 enrichment (FACE), measured seasonal changes in growth and nitrogen uptake of an inter-sub specific hybrid rice cultivar, *liangyoupeijiu* grown under two levels of CO_2 (ambient and elevated 200 μmol mol^{-1}) and two levels of N fertilization. The results showed FACE increased crop growth rate in the periods from transplanting to panicle initiation (PI), PI to heading and heading to maturity, which was mainly attributed to an increase in green leaf area index rather than the greater net assimilation rate. Grain yield increased greatly under FACE as a result of similar contribution by panicle number per unit area, grain number per panicle, and individual grain yield.

Studies of rice responses to CO_2 enrichment have focused on photosynthesis, water relation, phenology, organ formation, dry matter production and distribution, carbon and nitrogen metabolism, as well as grain yield, and its components, but very few studies have been carried out on the effect of elevated CO_2 on grain quality. The Japan FACE study indicated that the milling degree of *Japonica cv.* Akitakomachi with small panicle was significantly lower in elevated (CO_2) conditions with relatively lower nitrogen (N) application (9 g m^{-2}). The decrease of head rice percentage under elevated (CO_2) might attribute to substantial amount of assimilates retained in the alureone layer, which was removed during milling process. The CO_2 induced changes in grain appearance and deterioration in milling quality were closely correlated. The increase in grain chalkiness and decrease in milling suitability of rice under elevated CO_2 indicated softer (easily broken and ground) rice grains harvested under projected high (CO_2), which might affect market value of rice in the future. Amylose content is considered to be the key factor that contributes to the cooking and eating quality of rice. The higher the amylose content the more hardness in cooked grain. Amylose content is expected to increase with higher CO_2 content. Both FACE and chamber experiments indicated that elevated CO_2 significantly decreased protein and nitrogen concentration of rice grains, regardless of cultivar, N or P level applied to plants (Terao et al. 2005; Dong et al. 2002: Yang et al. 2007).

2.03.2.1.2 Water Limitation

The amount of water required to produce 1 kg of rice is 4000–5000 l of water leading to 50% water use efficiency. This can be increased to 80% if drained water is recycled. Although the Asian countries have abundant monsoon, it is expected that Asian countries will suffer from a water shortage by 2025 at the current rate of population and urbanization. Water logging is the main problem, followed by salinity, toxicity, and water pollution. Rice varieties differ greatly in their ability to tolerate aerobic soil and moisture deficit. The greatest ability to grow and produce some grain with chronic moderate water deficit is found in japonica varieties from upland ecosystems such as those found in hilly Southeast Asia and Africa (Mackill et al. 1996). The intrusion of sea water in coastal lands, leading to salt accumulation is a major problem. Water productivity of rice in terms of yield per unit of water evapotranspired ranges from a low of about 0.4 kg rice m^{-3} water evapotranspired to as much as 1.6 kg m^{-3} for wet seeded rice in the Philippines (Tuong 1999). Pollution of water resources, both surface water and groundwater, and of the air by industrial and urban emissions presents increasingly severe problems for rice production near urban and industrial centers. Its mitigation requires large-scale improvements in industrial and urban waste management.

2.03.2.1.3 Land Characteristics

In Asia, the average land holding of farmer is very poor. In addition to that, due to rapid urbanization and industrialization the cultivable land is also used for permanent construction and other purposes. Permanent water logging and rice monoculture have commonly caused microelement deficiencies, especially zinc and sulfur, and toxicities, notably iron. Though rice is adapted to waterlogged conditions because of the well developed aerenchyma that facilitates oxygen diffusion and prevents anoxia in roots, complete submergence can be lethal. Out of 40 million ha in Asia grown under rainfed lowlands, about 15 million ha are frequently damaged by submergence (Huke and Huke 1997). The effect of flash-flooding interacts with growth stage. Germination is highly sensitive to flooding. Zinc is the dominant element responsible for loss of fertility of wetlands followed by sulfur deficiency. Farmers through the application of chemical fertilizers give macronutrients, but neglect the supply of micronutrients. Eventually, the micronutrients become deficient leading to a nutritional imbalance in the soil.

2.03.2.1.4 Economics of Rice Production

Supply of water was the main factor during the green revolution in India. After that, the availability of water and necessary infrastructure for irrigation declined due to less investment. On the average, rice production activities employ 243 people per day per hectare in Bangladesh, 195 people per day per hectare in India, 156 people per day per hectare in Indonesia, and 60–80 people per day per hectare in the more mechanized production systems of the Philippines and Thailand (Pingali et al. 1997). Since 1995, international rice prices have declined markedly (Calpe 2003), while prices of production inputs such as fertilizers, other agrochemicals, labor, fuel, and rice machinery and equipment either increased or at best remained unchanged. This has been one of the major causes of poverty and hardship for many small farmers in developing countries. About 30% of the produce is lost as a result of poor land preparation, planting, harvesting, post-harvest handling, storage, and processing methods. The low level of engineering technology inputs in agriculture has been cited as one of the major constraint hindering the modernization of agriculture and food production including rice.

2.03.2.2 Biotic Stress

It is estimated that diseases and insects cause yield losses of up to 25% annually. With the increased adoption of direct seeding methods, weedy rice (*Oryza* sp.) has become another major weed in rice production. The economic impact of disease results in losses in productivity, the cost of disease management, and the economic penalty paid for having to grow less profitable alternative crops. The classic disease triangle recognizes the role of the physical environment in plant disease, as no virulent pathogen can induce disease on a highly susceptible host if weather conditions are not favorable. Relationships between weather and disease are routinely used for forecasting and managing epidemics and disease. The severity over a number of years can fluctuate according to climatic variation. Some diseases can cause more severe reduction in plant growth under twice ambient compared to ambient CO_2, at least in controlled environments. Among indirect effects, ozone can predispose plants to result in losses greater than by a pathogen alone, while the effect of UVB is inconsistent (Manning and Tiedemann 1995). More aggressive strains of pathogens with broad host range, such as Rhizoctonia, Sclerotinia, Sclerotium, and other necrotrophic pathogens may migrate from agricultural crops to natural plant communities.

2.03.3 Use of Crop Models for Yield Prediction

Crop production is very sensitive to climate with varying effects and with respect to different regions of the World (McCarthy et al. 2001). The IPCC (Third Assessment Report) analysis on climate impacts estimated a general reduction of potential crop yields and decrease in water availability for agriculture and population, in many parts of the developing world.

Crop growth simulation is a complex phenomenon as it involves interaction of soil, plant, weather, and management. These parameters have significant effect on each other and thereby on crop system as a whole. Dynamic crop growth modeling includes these parameters with the mechanisms and processes such as physiological, physicochemical, and meteorological leading to crop growth and yield simulation. The Wageningen group is the oldest working group for developing and applying crop models in agro-ecological research program. This group has developed and analyzed several crop models with the first effort of C.T. de Wit in the 1960s. The most popular and successful crop models of the Wageningen group include BACROS, LINTUL, SUCROS, ORYZA, WOFOST, INTERCOM, etc. (Ittersum et al. 2003). BACROS was the first crop simulation model developed by De Wit and co-workers of Wageningen University, and the DLO Research Institute for Agrobiology and Soil Fertility. This group also evaluated components of the model with the help of especially designed equipment and field experiments. The SUCROS (Simple and Universal Crop Growth Simulator) was the next outcome of the Wageningen group after the BACROS model. The SUCROS model was developed by Van Keulen (1982) and then Van Laar et al. (1997), which further formed the basis of the most popular crop models such as WOFOST, MACROS, and ORYZA. Next to that Spitters and Schapendonk (1990) introduced based LINTUL (Light Interception and Utilization) model for simulation of dry matter accumulation based on the light use efficiency.

MACRO (Modules of an Annual Crop Simulator) simulates the crop growth by emphasizing the biochemical aspect of plant physiology based on the concept of growth limiting factors (de Wit and Penning de Vries 1982; Penning de Vries and van Laar 1982). The input parameters for the growth simulation are solar radiation, maximum and minimum temperatures, precipitation, day length, vapor pressure, and wind speed. MACRO simulates the effect of CO_2 on photosynthesis.

RICEMOD (McMennamy and O'Toole 1983) is a rice growth simulation model which considers photosynthesis as a function of solar radiation, canopy structure, and the ratio of leaf nitrogen weight to area. The main input data for the model are precipitation, pan evaporation, maximum and minimum temperature, day length, and solar radiation. It also considers the soil–water balance relation and assumes optimum levels of nutrients for the crop simulation, but this model does not take into account the effect of natural hazards such as typhoons or pests.

RICESYS (Graf et al. 1990a,b) is a demographic model for rice growth and development. The main input parameters are temperature and solar radiation. This is the model which analyzes the crop–pest interactions and also provides a useful tool for integrated pest management studies.

INTERCOM is another crop model of the Wageningen group, which simulates the effects of pests and diseases. This model considers the crop–weed competition from the partitioning of the growth-defining (light) or limiting (water and nutrients) resources over the competing species and the efficiency with which each species uses the resources to simulate the crop growth and helps to make a decision for the use of pesticides (Kropff and Van Laar 1993).

The ORYZA1 was developed by Kropff et al. of the Wageningen group in the year 1994. The main parameters of this crop simulation model are light, temperature, and other factors, which affect the phenological, morphological, and physiological processes of the crop. The inputs for the model are latitude, daily weather data (global radiation, maximum and minimum temperature), and seeding date. It simulates the daily dry matter production and the rate of phenological development of the crop from these inputs and integrates growth rates over time to calculate dry matter production throughout the growing season.

Hoogenboom et al. (1994) developed a Decision Support System for Agrotechnology Transfer (DSSAT), which integrates various crop simulation models for grains, legumes, cereals, vegetables, and oilseed crops with weather, soil, and experimental databases. It includes various analysis programmes to apply the crop models for decision making pertaining to short and long practical and strategic planning. Under the framework of the DSSAT v3.5 CERES Model is designed to simulate crop growth and development of different crops, which simulates the yield for different soil and nitrogen content conditions, for alternative technology, and for new growing sites. The weather inputs for this model are daily solar radiation, maximum and minimum temperature, and precipitation. It can simulate the impact of diseases on rice yield. The CERES rice model considers photosynthesis as the function of leaf area index and expresses in terms of daily biomass production. The phenological growth and development in the CERES models are mostly cultivar-specific and the model simulates the growth and development stages by the genetic coefficients, which are determined by the photoperiod, thermal time, temperature response, and dry matter partitioning.

The World Food Study (WOFOST) model (Supit et al. 1994) is a one-dimensional, mechanistic, and site-specific crop model for wheat, grain maize, barley, rice, sugar beet, potato, field bean, soybean, oilseed rape, and sunflower. This crop model basically evaluates the crop yield and variability for different climate scenarios and can also be used to estimate crop production, indicate yield variability, evaluate effects of climate change or soil fertility changes, and determine limiting biophysical factors. Weather and soil data are the main inputs for this model, which include rainfall, temperature, wind speed, global radiation, air humidity, soil moisture content at various suction levels, and data on saturated and unsaturated water flow. WOFOST simulates the daily growth of a specific crop based on the light interception and CO_2 assimilation as the growth driving processes and crop phenological development as the growth controlling process of that crop.

CropSyst is basically a process based, multi-year, multi-crop, daily time step cropping system simulation model (Stockle and Nelson 1999; Stockle et al. 2003). This model simulates the soil water budget, soil–plant nitrogen budget, crop growth and development, residue production and decomposition, and soil erosion. The main model inputs include daily weather data, dates and amounts of products applied for each fertilization and irrigation event, sowing date, hydraulic characteristics of the soil profile, crop parameters, and initial conditions of the soil profile, such as crop residues, water content, mineral nitrogen, and organic matter. The main outputs of the CropSyst model are above ground biomass, leaf area index, root depth, soil water, and nitrogen balance. CropSyst simulates the crop development for the whole canopy, which is a function of thermal time accumulated between a base temperature (Tbase) and a maximum temperature (Tcutoff). CropSyst was developed to simulate the growth and development of potentially all herbaceous crops.

Water Accounting Rice Model (Confalonieri et al. 2006) is crop model software which simulates paddy growth and development based on temperature and radiation data. It also simulates biomass partitioning, floodwater effect on temperature, spikelet sterility, floodwater and chemicals management, and soil hydrology of the crop. WRAM is an integration of four tools, namely (1) Monte Carlo–based sensitivity analysis, (2) automatic calibration (based on simple and genetic evolutions of the simplex optimization method), and (3) the evaluation of model performances. The key concept of this rice growth simulation model is that of radiation use efficiency (RUE), a parameter, which is used to convert intercepted solar radiation into above ground biomass.

2.03.4 Climate Adaptation

Adjustments in the ecological, social, or economic systems are made in response to actual or expected stimuli and their effects or impacts. This term refers to changes in processes, practices, and structures to moderate potential damages or to benefit from opportunities associated with climate change (IPCC 2001). Reactive adaptations are those that occur after the impacts of climate have been experienced, while anticipatory adaptations are pro-active, undertaken before the impacts are fully felt. Planned adaptations are generally anticipatory, but can also be reactive (i.e., adaptations are planned to be implemented once variations in local and regional climate effects are experienced) (Klein and Tol 1997). India is vulnerable to any increase in occurrence of extreme climatic events. Climatic influences can result in a hindrance in development and potential changes in social and environmental conditions. Technology transfer can play a key role in the modernization of processes in addition to government initiatives. Historically, farming systems have adapted to changing economic condition, resources availability, and technology. For adaptation measures, the authors first chose the adjustment of planting dates. Shift in current planting date and induced temperature tolerance to spikelet sterility were found to be suitable adaptation measures for eastern India (Krishnan et al, 2007). Similarly, Swain and Thomus (2010) reported advancement in planting date by 10–30 days and varietal adaptation for reducing the climate change impact on rice production in West Bengal, India. For areas, those are characterized by cold winters from October to April like northern China, the planting date is adjusted by different field experiments. The potential yields were lower under the conventional planting date, due to the effect of increased temperatures on spikelet sterility. Different experiments were conducted to take the advantages of longer growing seasons in temperate climates. The growing period was widened from 120 to about 200 days, from normal planting date of around 1 May, so that both earlier and later sowings become feasible. The wider sowing window allowed the possibility of two rice crops per year. The first crop is sown between the beginning of February and the end of March, with the second being sown in June or July and total annual production was found to be much higher than the single cropping. They also suggested the changes in sowing dates to avoid the high temperatures around flowering that cause spikelet sterility. International Rice Research Institute (IRRI) is developing certain adaptations via plant breeding such as introduction of early morning flowering (EMF) trait to the varieties/screening of varieties which have uniqueness of EMF when atmosphere is cool. Such EMF traits have been observed in *O. minuta* and *O. officinalis* (Sheehy et al. 2007). Introduction of high temperature tolerant gene to a particular variety is also good option for climate change adaptation (Yoshida 1981; Prasad et al. 2006; Jagadish et al 2008).

Sustainable management of soil involves creating a positive C budget, a balanced nutrient–elemental budget, diverse soil faunal and floral activities including those of earthworms and microorganisms, and creating a favorable soil reaction (pH). The soil organic matter is the key element in soil management. The soil organic matter holds significant amount of moisture thereby reducing the runoff. It helps in stabilizing the soil structure. Conservation agriculture and organic agriculture that combine zero or low tillage and permanent soil cover are major adaptation options promoted by FAO for their ability to increase soil organic carbon, reduce mineral fertilizers use, and reduce on farm energy costs.

Risk transfer mechanisms should be included in adaptation strategies from the national to the household level. This can include crop insurance or diversified livelihoods such as integrated aquaculture–agriculture systems which allow activities to shift in response to changes in the suitability of land and availability of water to produce food. Economic diversification within sectors reduces the dependency on climate-sensitive resources, particularly for countries that rely on narrow ranges of climate-sensitive economic activities.

2.03.5 Water Management

Wider use of technologies to harvest water and conserve moisture along with higher water use efficiency is necessary. Managing water to prevent erosion, runoff, water logging, and seepage will help in reducing leaching of nutrients. On-farm water management and supplementary irrigation are necessary to avoid drought. Micro-irrigation, especially sub-surface drip irrigation, is a modern innovation to enhance water use efficiency.

Water productivity in continuous flooded rice areas was typically 0.2–0.4 g grain per kg water in India. The water saving irrigation increased water productivity up to a maximum of 1.9 g grain per kg water, but decreases yield. Irrigated rice is also regularly affected by water stress due to in adequate irrigation water supply. Most water management research has been focused on flooded rice, and limited work has been done on intermittent irrigation with returning aerated soil conditions. The major outflows of water from the rice field are evaporation, transpiration, seepage, percolation, and over bund runoff flow. The seepage and percolation account for about 50-80% of the water input (Bouman et al., 2005). The recent introduction of water saving irrigation technique such as reducing the depth of pounding water, system of rice intensification (Krupnik et al., 2012), alternate wetting and drying (Dong et al., 2012; Yao et al., 2012), and keeping the soil just saturated (Yadav et al., 2011a,b)are options to minimize the seepage and percolation loss of water from rice field.

Soil moisture deficit reduces plant height and tiller number. However, reduction in crop growth and yield depends on degree and duration of water deficit and growth stage of crop. (Raamakrishnayya and Murthy 1991). The effects of water stress on photosynthesis, growth, and development are equally or more important than effects on other processes, especially in annual crops. Rice is more susceptible to moisture stress during early seedling and flowering stages than other stages of growth and generally the reproductive stage is more affected than the vegetative stage.

The system of rice intensification (SRI) developed in Madagascar over a 20-year period and synthesized in early

1980s by the late Father Henri de Laulanie, S.J. Experience with SRI method suggests that average rice yields can be about double and water requirement is half to that of conventional cultivation method. The seedlings at the age of 12–14 days and at 20 cm × 20 cm spacing are transplanted. Since the soil is kept moist only during the vegetative growth phase and only minimal water is kept during the reproductive phase, SRI results in water savings to an extent of 35–40% compared to the conventional method. This method has a fair number of advantages, namely increased tillering, profused root growth, reduced seeding, and fertilizer requirement. However, the success of this method depends upon the water management and accuracy in transplanting.

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2.04 Understanding the Impacts of Climate on Perennial Crops

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Glossary

Chilling requirement The minimum amount of cold temperatures needed for a plant to break winter dormancy and resume growth in the spring.

Dormancy A period of reduced plant activity and growth.

Downscaling The process of adding information at scales smaller than the original spatial resolution or temporal aggregation period.

Fall hardening The gradual process by which a plant becomes tolerant of freezing temperatures.

Growing degree days (GDDs) A measure of heat accumulation, calculated as the difference between the daily mean temperature and a specified base temperature. GDDs are frequently used in agriculture to estimate planting times and approximate dates of crop development stages.

Perennial crops Agricultural commodities with life spans of two or more years.

Phenology The growth stages of a plant.

Poikilothermic Organisms whose growth and development is primarily temperature dependent.

Veraison The onset of ripening.

2.04.1 Introduction

Perennial crops, including the commercial production of fruits and nuts, play important dietary and economic roles at local, regional, national, and international scales. The vulnerability of these commodities to climate has not been as widely studied as compared to annual crops, in spite of their greater relative exposure to fluctuating weather conditions due to their perennial nature. In contrast to many annual crops, the spatial extent of perennial crops across the landscape is relatively limited. Rather, perennial crop production is frequently constrained to areas with unique local or regional climates that are often influenced by topographic position, proximity to water bodies, or the presence of mesoscale atmospheric circulations and weather conditions such as frequent fog that modify the local climate. This limited spatial extent of production regions contributes to the climate vulnerability of perennial crop production. Furthermore, orchards require substantial initial investment and the typical lifetime is on the order of 20–30 years, limiting adaptation options and the time scales at which adaptations can be implemented.

Perennial crops present numerous challenges for climate impact and vulnerability assessments. As summarized by Lobell and Field (2011), multiple critical physiological stages must be considered, process-based crop models remain largely unavailable or poorly developed for perennial crops, and the slow growth of perennials makes experimental warming trials less feasible than for annual crops. Also, as pointed out by White et al. (2006), climate assessments for perennial crops must have a fine spatial resolution to resolve subregional scale climate–crop relationships. In spite of these constraints and challenges, a substantial body of literature has evolved on climate impacts on perennial crops that covers multiple production areas worldwide. Based on the frequency of published articles, the fruit crops most investigated are wine grapes, apple, cherry, citrus, peach, and apricot. Numerous other fruit commodities have also been studied including kiwi, mango, pear, pineapple, plum, and strawberry. Almonds and walnuts are the two most widely investigated nut tree commodities.

This chapter reviews prior research examining the impacts of climate on perennial crops. The goals are to (1) highlight vulnerable growth stages and industry components, (2) describe the common methods and analytical techniques used to investigate climate impacts on perennial crops, (3) summarize, based on published literature, the current understanding of temporal trends in freeze risk, heat stress, and the timing of growth stages, and (4) provide our perspective on existing knowledge gaps and recommendations for future research.

2.04.2 Climate Vulnerability of Perennial Crop Production

In general, perennial trees in temperate and cool subtropical climates lose their leaves and begin a cold hardening stage in early fall before becoming dormant in late fall. In some plants, the cessation of growth during fall is triggered by shorter day length, whereas others respond to colder air temperatures. Buds remain dormant or in the stage of 'rest' due to internal physiological blocks (i.e., inhibitors) that prevent their development even under ideal conditions for growth. These physiological blocks are removed when buds are exposed to chilling temperatures above freezing for some weeks. The chilling requirement is often fulfilled in winter for both high- and low-latitude species. After chilling is completed and buds are no longer in a state of 'rest,' they become 'quiescent' and respond to heat accumulation. Cold temperatures during the quiescent period prevent bud growth, whereas buds become active losing much of their hardiness when the temperature becomes favorable for growth. Perennial crops are particularly vulnerable to cold damage at three distinct stages: (1) in the fall before the tree is adequately hardened, (2) during the winter dormant period when severe cold events can cause injury to woody tissue, and (3) during spring when temperatures slightly below freezing may kill flower buds following the loss of cold hardiness (Raseira and Moore 1987). Although cold damage in fall and winter can cause permanent injuries to perennial trees, they are usually less frequent, and have a smaller effect on year-to-year variability in yield, compared to springtime freeze events.

Production is also influenced by other climate factors, such as the amount of plant available moisture in the soil profile, conditions during pollination, the occurrence of prolonged and/or extreme heat or drought events, and the frequency of hail during the growing season. Additionally, weather conditions, including temperature and humidity, contribute to the risk of insect pests and plant diseases, which also affect orchard and vineyard productivity.

An initial step in a climate assessment for perennial crops is the identification of the critical growth stages and related climate factors for the crop in question (Figure 1). Although

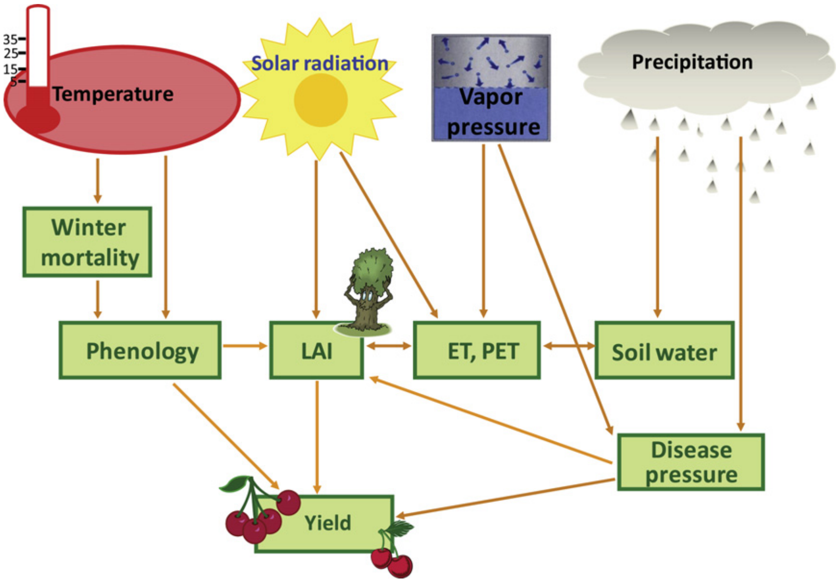

Figure 1 Weather and climate influence a number of aspects of perennial crop development and yield. This cartoon illustrates the potential impacts of four climate variables on sour (tart) cherry production in the Great Lakes region of North America. The cartoon was prepared by Andresen, J. A., J. R. Black, C. Zavalloni, and J. M. Bisanz at Michigan State University for the Pileus Project (http://www.pileus.msu.edu/), and is used here with their permission.

these factors will vary by crop, past studies have highlighted winter chill fulfillment, changes in springtime freeze risk, pollination constraints, heat stress, and enhanced disease and insect pest pressure as particularly contributing to the climate vulnerability of perennial crops.

2.04.2.1 Winter Chill Fulfillment

As noted above, for many commercial perennial tree crops (e.g., apples, cherries, and peaches), a chilling requirement must be met to break winter dormancy and resume growth in the spring (Luedeling and Brown 2011). When chilling requirements are not met, foliation is delayed and flowering is irregular and occurs over a longer period, resulting in varying fruit sizes and maturity stages at the time of harvest and even in poor pollination if synchrony of male and female flowering is required for pollination (Byrne and Bacon; Luedeling et al. 2009). Thus, possible warming raises concerns regarding crop quality and yield, if perennial trees do not fulfill their chilling requirements.

2.04.2.2 Springtime Freeze Risk

For many current areas of perennial crop production, damaging springtime temperatures is the single most important climate-related risk factor (Flore 1994). Springtime freezes can be classified as either an inversion (radiation) freeze or a wind (advection) freeze (Winkler et al. in press). Estimating the temperature at which damage occurs to flower buds is challenging, due to the confounding factors of growth stage and ambient conditions, and published temperature thresholds (e.g., Longstroth 2007) are likely a more appropriate reference for inversion freezes compared to wind freezes. Damages associated with wind freezes may occur at warmer temperatures than the published temperatures, especially if the period of cold temperatures is prolonged and/or the flower buds are wet due to precipitation (Longstroth 2007).

Considerable uncertainty exists regarding the future susceptibility of perennial crops to below freezing temperatures when preceding crop development is considered. Early spring warm-ups may result in greater freeze risk if flower buds are at a more advanced stage of development at the time of the last spring freeze. On the other hand, if the date of the last spring freeze advances to an earlier date in synchrony with bud development, spring freeze risk may not change or even decrease. Thus, a warmer climate cannot be assumed to bring more favorable conditions for perennial crops that currently are vulnerable to springtime freeze damage.

2.04.2.3 Pollination Constraints

Conditions favorable for pollination vary with species. For example, Lobell and Field (2011) argue that below average temperatures during the bloom season lead to a longer pollination period for almonds, as the stigma is receptive to pollen for longer periods of time. Consequently, warming during the bloom period could contribute to reduced yield. On the other hand, pollination of highbush blueberry in the Great Lakes region of North America is negatively impacted by cool, moist conditions (Tuell and Isaacs 2010). Bees are essential for pollination, and their activity is reduced under unfavorable weather conditions such as temperatures below 12 °C and wind speeds greater than 25 km h^{-1} (Thomson 1996). Warmer temperatures, if also accompanied by light winds and dry conditions, could result in greater pollination for this region and crop type.

2.04.2.4 Heat Stress

Heat and drought spells during the growing season are a concern for most perennial crops, as temperature and moisture availability directly influence photosynthesis, fruit size and quality, and harvest time. As summarized by Moretti et al. (2010), more heat can lead to higher sugar content (e.g., apples, grapes), lower levels of tartaric acid (e.g., grapes), lower fruit firmness (e.g., avocado), and higher antioxidant activity (e.g., strawberries). Higher temperatures can additionally reduce vitamin content of some fruit crops (McKeon et al. 2006). Physical damage is also possible including burning of walnuts (Baldocchi and Wong 2008) or sunburn and loss of texture in apples (Ferguson et al. 1999). When wine grapes are exposed to prolonged periods of high temperature, plant heat stress can lead to premature veraison (i.e., onset of ripening), the separation of berries from vines, enzyme inactivation, and failure of flavor ripening (White et al. 2006).

2.04.2.5 Disease and Insect Pest Damage

A confounding factor when considering climate impacts on perennial crop production is the frequency and severity of insect pests and plant diseases. Insect pests are poikilothermic; that is, their growth and development is primarily temperature dependent. Thus, the number of insect generations per year and their timing with respect to plant development stages are sensitive to a perturbed climate. For example, annual monitoring of codling moth (*Cydia pomonella*) in Germany's northernmost apple growing region (Lower Elbe valley) points to the occurrence of a partial second generation during warm years such as 2006, 2008, and 2010, and a climate impact analysis suggests possible future increases in the annual number of codling moth generations in all German fruit growing regions (Chmielewski et al. 2009). Also, increased insect pest populations could lead to early leaf abscission, which in turn contributes to an early loss of photosynthetic capability and therefore lower accumulation of total carbohydrates in perennial organs. For example, in sour cherry early defoliation delayed acclimation in the fall and induced a more rapid deacclimation in the spring, reducing bud survival and fruit set (Howell and Stackhouse 1973).

The severity of plant disease outbreaks is influenced by moisture conditions in addition to temperature. For example, Ladányi et al. (2010) found that rain during the bloom period promotes bacterial and fungal diseases in sour cherries. Further, *Diplodia seriata*, a cause of black rot of apples, is a new pathogen in the Lower Elbe valley whose appearance is probably associated with higher temperatures and more frequent rainstorm events during the the vegetation period (Weber 2009).

Future changes in plant development and insect and disease pressure might necessitate different approaches for the use of pesticides and disease protection management strategies

(Khanizadeh 2007). A number of current management strategies, such as chemical sprays, are restricted to certain growth stages or specified times before harvest, and changes in the timing of insect life cycles or disease occurrence with respect to crop growth stages could make these strategies no longer viable Winkler et al. (2002).

2.04.3 Nonclimatic Contributions to Vulnerability

Climate is not the only consideration when assessing the long-term viability of perennial crop production. Economic and social factors must also be considered. Specific concerns will vary with crop type and location, but most industry stakeholders must contend with changes in consumer demand, competing land uses, and competition with other production regions. The sour (tart) cherry industry in the United States is used here to illustrate these concerns.

While relatively small in scope, sour cherry production has major economic impacts at the local and regional levels. Production in the United States occurs primarily in the lake-modified zones surrounding the Great Lakes. In 2009, 292 million pounds of sour cherries, or 80% of the national total, were produced in Michigan, New York, Pennsylvania, and Wisconsin (NASS 2011). Of this amount, 266 million pounds were produced in Michigan alone.

Changes in consumer demand have been a particular concern for the sour cherry industry in the United States. The majority of product exchange is as processed products, with frozen sour cherries an intermediate product destined for use in the further processed ingredient and bakery industries (Thornsbury and Woods 2005). However, changes in American dietary patterns have reduced the demand for sour cherries by the bakery industry, forcing industry stakeholders to search for alternative uses of their product. The Cherry Marketing Institute, located in Michigan, has launched a ‘Go red instead’ campaign, advertising the high antioxidant content and health benefits of sour cherries (Cherry Marketing Institute), and the health foods industry is becoming an increasingly important commercial outlet for sour cherry production.

Competing land uses are also a concern. Orchards are typically located on hilltops and slopes near the Great Lakes shoreline in a scenic environment and sought after area for vacation homes. Many local planning organizations have recognized the contribution of the orchards to the allure of the local environment with some areas putting in place regulations to limit housing development, but, nonetheless, development pressure contributes to the vulnerability of the sour cherry industry in the Great Lakes region. Furthermore, sour cherry production is competing for orchard sites with wine grape production, which has increased substantially in size over the past several decades.

Competition with other production regions is also a growing concern. Historically, the United States imported very little in terms of sour cherry products, relying instead on a nationally produced product. However, after the near-complete crop failure in northwest Michigan in 2002 due to a springtime wind freeze, sour cherries were imported to the United States to sustain current markets, with most fruit imported from Poland – the current world leader in sour cherry exports and where the sour cherry industry has recently rapidly expanded (Thornsbury and Woods 2005). Although imports from Poland and other producing regions have since declined with improved production in Michigan and other cherry producing states, sour cherry imports remain at a higher level than before the 2002 crop failure (Thornsbury and Woods 2005). Importation remains elevated in part because Schatten Morello, the sour cherry variety grown in Poland and several other European production regions, differs from the cultivar Montmorency primarily grown in Michigan in terms of fruit color, taste, and other physical characteristics. Thus, the two cherry cultivars are not perfect substitutes for each other.

Additional nonclimatic factors that can contribute to the vulnerability of commercial sour cherry production and other perennial crops include uneven changes in wealth effects, influencing patterns of supply and mix of goods demanded, and political actions in response to environmental or trade concerns that lead to changes in subsidies (Winkler et al. 2010). These factors, along with changes in consumer demand, land use pressure, and competition with other production regions, may make investments in perennial crops unappealing to the individual producer.

2.04.4 Methods and Models for Assessing Climate Impacts on Perennial Crops

In contrast to assessments for annual crops, where the focus is often on potential changes in yield as estimated from well-known process-based models, climate assessments for perennial crops heavily rely on empirical relationships developed between climate observations and plant phenology, and, less frequently, between climate observations and yield. A number of empirical approaches have been applied, all of which have strengths and weaknesses that must be considered when interpreting the outcomes of assessment studies. Below we highlight several analysis and modeling approaches that have been frequently utilized for assessments of climate impacts on perennial crops. These methods, along with climate inputs and typical outcomes, are summarized in Figure 2.

2.04.4.1 Critical Thresholds, Growing Degree Days, and Agro-Climatic Indices

Critical thresholds represent perhaps the simplest approach for evaluating climate impacts, and many applications appear in the literature (e.g., Winkler et al. 2002; Zavalloni et al. 2006a,b; Rochette et al. 2004). As a more recent example, Ladányi et al. (2010) argued that the 10 days before and during bloom had the greatest impact on sour cherry quality and yield in Hungary and explored the effect of changes in the frequency of several critical thresholds. These thresholds were selected to assess freeze risk and conditions for pollination, and included the number of days with minimum temperatures below 0 °C and precipitation greater than 5 mm. The advantage of critical thresholds is their modest data requirements and computational costs, whereas a disadvantage is the difficulty in identifying appropriate threshold values. Critical thresholds can vary with variety and cultivar, and field trials and growth chamber

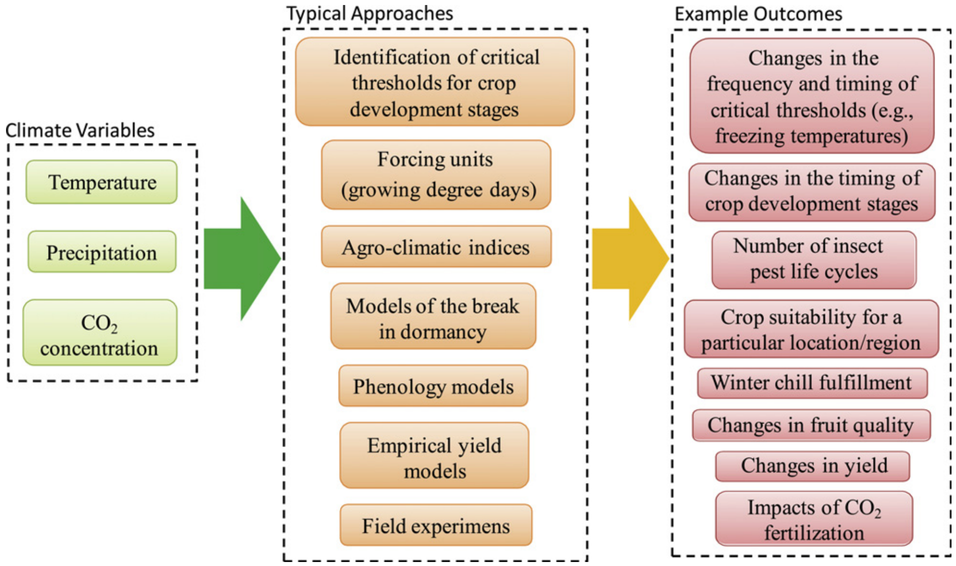
Climate Variables
Temperature
Precipitation
CO_2 concentration
Typical Approaches
Identification of critical thresholds for crop development stages
Forcing units (growing degree days)
Agro-climatic indices
Models of the break in dormancy
Phenology models
Empirical yield models
Field experimens
Example Outcomes
Changes in the frequency and timing of critical thresholds (e.g., freezing temperatures)
Changes in the timing of crop development stages
Number of insect pest life cycles
Crop suitability for a particular location/region
Winter chill fulfillment
Changes in fruit quality
Changes in yield
Impacts of CO_2 fertilization

Figure 2 Typical methods and analytical techniques used to investigate climate impacts on perennial crops, along with frequently used climate inputs and example outcomes.

experiments are often unavailable for the crop variety or cultivar of interest.

Growing degree days (GDD), typically calculated as the difference between the daily mean temperature and a specified base temperature, have also been widely used in assessment studies for perennial crops, particularly to estimate the timing of different phenological stages (e.g., Nemani et al. 2001; Winkler et al. 2002; Zavalloni et al. 2006a,b) (Figure 3). For example, the Baskerville-Emin method (1969) was used to calculate growing degree days (base value 5 °C) beginning from 1 January for the sour cherry production regions of Michigan (USA), and early bud development (e.g., 'side green') was estimated to occur when ~150 growing degree days was reached (Winkler et al. in press). The degree day concept can also be used to evaluate changes in cold intensity and duration, as shown by Rochette et al. (2004). In this case, 'cold' degree days were defined as the degree days below a base value of $-15\,^{\circ}\mathrm{C}$ and were accumulated for the period 1 August–31 July. Additionally, some authors have employed modified degree day calculations, such as the Huglin Index (Duchêne and Schneider 2005) which weights daily maximum temperature more than minimum temperature in order to better represent species-specific development requirements, or biologically effective degree days (BEDD) that restrict the maximum heat accumulation for a particular day to emulate the reduction in growth rate at high temperatures (Hall and Jones 2008). Blümel and Chmielewski (2012) found that incorporating a day length term into a GDD model markedly improved projections of the timing of fruit tree blossom. Often times critical thresholds and heat accumulation are considered jointly; for example, growing degree day accumulation at the time of the last spring freeze (e.g., the last occurrence in spring of minimum temperature ≤ 0 °C) can provide an indication of temporal changes in crop susceptibility to damaging cold temperatures (Winkler et al. 2012, in press).

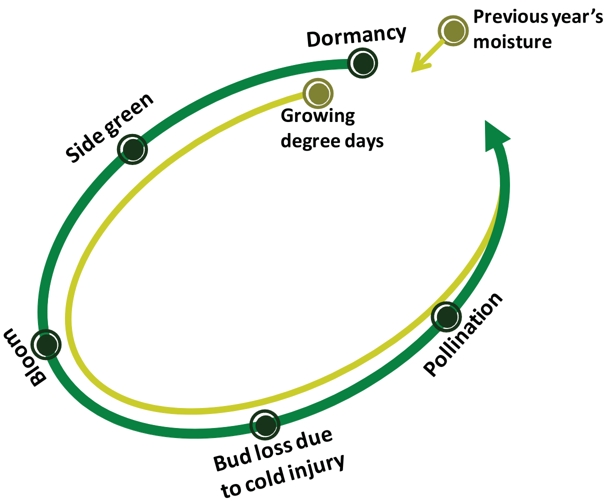
Dormancy
Previous year's moisture
Side green
Growing degree days
Bloom
Pollination
Bud loss due to cold injury

Figure 3 Growing degree days (also referred to as forcing units) are frequently used to estimate growth stages of perennial crops. In this example for sour cherry production, growing degree days are used to estimate the (1) timing of side green (a critical growth stage that occurs soon after bud swell), (2) the timing of flower bloom, (3) crop development at the time of last spring freeze and consequent bud loss, and (4) the timing of pollination. This image was prepared by Andresen, J. A., J. R. Black, C. Zavalloni, J. M. Bisanz, and H. K. Min at Michigan State University for the Pileus Project website (http://www.pileus.msu.edu/) and used here with their permission.

Agro-climatic indices are simply the expression of one or more climate variables in terms reflective of conditions important to crop development. These indices are often used to judge the suitability of a particular region for crop production, and have been a particularly popular approach for assessing suitable areas for quality wine production (e.g., Jones and Davis 2000; Hall and Jones 2008). As an example, White et al.

(2006) developed a nominal, four-category index for identifying premium wine grape producing areas in the United States based on the frequency of hot and cold days, diurnal temperature range in the growing and ripening seasons, and average temperature and heat accumulation during the growing season.

2.04.4.2 Modeling the Break of Dormancy

Models used to estimate whether perennial crops have met their chilling requirement for break of winter dormancy are collectively referred to as 'chill models.' Several chill models currently exist, although all are based on the concepts of growing degree days and critical thresholds. A commonly used but relatively simple model is the Chilling Hours Model, also referred to as the Weinberger Model (Weinberger 1950). This model requires hourly temperature measurements as input, and chilling is simply calculated as the sum of hours when the temperature falls between the thresholds of 0 and 7.2 °C. The user needs to fix the time period for the summation, which can vary by location and variety, although a frequent summation period (for Northern Hemisphere locations) is 1 November–1 March (Luedeling et al. 2009). In contrast, the popular Utah Model (Richardson et al. 1974) assigns different chilling efficiencies to different temperature ranges (Luedeling and Brown 2011), and includes the concept of negative chilling accumulation or chilling negation with temperatures above 15.9 °C assigned negative chill units (Byrne and Bacon). The Dynamic Model (Erez et al. 1990) represents a more complex formulation. The underlying assumption is that dormancy completion depends on the level of a dormancy-breaking factor that accumulates in flower buds (Erez et al. 1990). As summarized by Luedeling et al. (2009), initially an intermediate accumulation product is formed in a process promoted by cold temperatures, with warm temperatures able to destroy this product. Low temperature efficiency in releasing buds from rest follows an optimum curve where the maximum efficiency is between 6 and 10 °C (Erez and Lavee 1971). Higher temperatures produce negative effects and result in negation of a certain amount of hours of chilling units depending on the species and cultivar (Erez et al. 1979). Once a critical level of the intermediate product is amassed, it is irreversibly transformed into a Chill Portion, which can no longer be destroyed (Luedeling and Brown 2011.) An advantage of the Utah Model and the Dynamic Model over the older Chilling Hours Model is that end and start dates for chilling accumulation do not need to be prescribed, as both models can account for the reversibility of the chilling process when temperatures are high (Luedeling et al. 2009).

A major concern of all chill models is their applicability outside the region for which they were initially developed, especially as the models are often extrapolated to other locations with little or no change in the original parameters and critical temperatures. Luedeling and Brown (2011, p. 411) recently expressed their concern that users "assume that the choice of chill model is not important and that estimates of species chilling requirements are valid across growing regions." This concern is particularly critical for climate assessments, as biases resulting from the misapplication of chill models may provide a misleading interpretation of plausible future changes in the spatial distribution of production regions. Recent comparisons of the output of the chill models at multiple locations worldwide provide credence to this concern and suggest that site-specific correction factors are likely needed in order to facilitate spatial comparisons (Luedeling and Brown 2011).

Another constraint when applying chill models is the need for hourly temperature data. Hourly observations are available for a much smaller subset of climate observing stations compared to daily temperature observations. Consequently, subregional variations in chill units often cannot be captured by the coarse spatial resolution of hourly observing networks, particularly in areas of complex topography where temperature is highly associated with landscape position (i.e., aspect, elevation).

2.04.4.3 Estimating the Timing of Growth Stages

Phenological modeling is an important component of many climate assessments for perennial crops. Some phenological models are purely statistical in character such as the model developed by Zavalloni et al. (2006a) that relates flower bud phenological stages for sour cherries to growing degree accumulations. Others are somewhat more mechanistic in concept and attempt to simulate the processes of chilling and subsequent heat accumulation (e.g., Chuine et al. 1998). Recently, Chmielewski et al. (2011) evaluated the ability of five representative phenological models to estimate apple blossom in Germany. The comparison included a phenological model that assumes chilling is completed by 1 January and estimates blossom time based on a temperature forcing rate function, a slightly more complex model that assumes forcing temperatures are not effective until chilling is met and estimates both chilling rates and a forcing rate function, two 'parallel' models that assume chilling and forcing can occur simultaneously but differ in terms of how the chilling and forcing rates are calculated, and a simple statistical model employing mean temperatures for the period February–April as predictors of apple blossom. All five models were found to satisfactorily simulate the beginning of apple blossom for a wide range of apple cultivars, although the error was smallest for the combined chilling–forcing models. Furthermore, all five models performed well even though daily, rather than hourly, temperature series were used as model input. These findings suggest that at least some phenological models can be employed to estimate the beginning of blossom for multiple cultivars and geographic regions, although further evaluation for a larger number of crops and locations is needed. Recently developed phenological models that incorporate day length, in addition to chilling and heat accumulation (Blümel and Chmielewski 2012), appear to perform well in different geographic regions and have utility for climate assessments (Matzneller et al. 2012, manuscript submitted to *Agric. Forest Meteorol.*).

2.04.4.4 Empirical Yield Models for Perennial Crops

As previously noted, few process-based yield models exist for perennial crops. One exception is the CropSyst modeling system, a relatively simple generic (i.e., multi-crop) daily time step simulation model that includes an orchard–vineyard module (Stöckle et al. 2010). As noted by the developers, the extension of CropSyst to perennial crops is still in its early stages, and its performance across a wide range of perennial crops and locations remains largely untested. Empirical methods continue to be the primary approach for estimating yield for perennial crops, although the resulting models are specific to an individual location and crop type (or even cultivar). The development of empirical yield models has proven to be a demanding, often frustrating, undertaking. Two recent papers, describing the development of state-level (Lobell et al. 2006) and county-level (Lobell and Field 2011) empirical yield models for perennial crops in California, highlight the many challenges in empirical yield model construction. Yield models were developed at two very different spatial scales, since, as pointed out by Lobell and Field (2011), the spatial scale (e.g., station, county, state) for model development is not intuitive, and is often dictated by the availability and spatial coverage of weather, production, and yield measurements rather than by theoretical and statistical considerations. An advantage of the county-level models is the greater range of values for the predictor variables (monthly temperature and precipitation for the California models), whereas an advantage of the state-level models is that they are not as susceptible to omitted variable bias compared to the county-level models, where variations between counties may be a function of other factors (e.g., soil) besides climate (Lobell and Field 2011). Another challenge is that the explained variance of the empirical yield models is often very modest. In fact, Lobell and Field (2011) found that the county-level empirical relationships were significant for only 8 (almonds, wine grapes, strawberries, hay, walnuts, table grapes, freestone peaches, and cherries) out of the 20 perennial crops for which models were developed. Even for these eight crops, the explained variance when the models were applied to a test period hovered only around 20%. One reason for the low explained variance is that mean values of temperature and precipitation, which are commonly used predictors, are not sufficiently capturing the physical processes contributing to yield variations. Furthermore, the spatial aggregation masks considerable spatial variability in climate conditions and in the quality of orchard and vineyard sites. The choice of spatial aggregation level can also result in different interpretations of the impacts of climate on yield. Lobell and Field (2011) found, for instance, that the county-level model for almonds suggested a small beneficial effect of warming temperatures on yield, whereas the state-level model suggested a negative effect. These differences led Lobell and Field (2011) to argue for greater effort to verify the signs of model coefficients, including surveying growers to obtain their input on the importance (and direction) of weather variables on yield.

Empirical yield models have numerous additional constraints – management practices are usually considered constant, temporal trends in yield due to improved technology need to be removed, CO_2 fertilization is rarely included, linking statistical relationships to physical processes is difficult, and, like all empirical models, the validity of the yield models is questionable outside the range of the data used in the model development (Lobell and Field 2011). This latter issue is of particular concern for climate studies, as the range of values of the predictor variables, particularly maximum and minimum temperature, could shift in the future.

2.04.4.5 Field and Greenhouse Experiments

In addition to the empirical and modeling approaches described above, a limited number of field and/or greenhouse experiments have been conducted for perennial crops, particularly to investigate the impacts of changes in carbon dioxide (CO_2) concentrations on crop growth and development. For example, Idso et al. (1991) exposed sour orange trees to elevated CO_2 concentrations to investigate changes in photosynthesis rate, whereas Allen and Vu (2009) considered the impact of CO_2 enrichment on leaf and root development for sweet orange trees.

2.04.5 Perennial Crop Production and Historical Climate Variability

Synthesis of the numerous studies that have investigated the impacts of historical climate on perennial crops is challenging as differences are expected by geographic region and crop type. Most analyses of the influence of historical climate variability focused on the timing of phenological stages, and, in general, these studies found that crop growth has advanced earlier in the year. For example, an increase of 0.06 °C per annum in average springtime temperatures appears to be associated with an earlier and shorter period between budburst, flowering, and harvest of wine grapes in France (Duchéne and Schneider 2005). Similar results were found by Jones and Davis (2000), who observed a shortening of growth intervals and lengthening of growing season for wine grapes.

Additionally, warming trends in Japan appear to have contributed to an advancement in phenology for apple and cherry trees (Fujisawa and Kobayashi 2010; Primack et al. 2009) and to earlier flowering dates for apricots (Doi 2007). Similarly, earlier flowering times for apples and pears in France have been observed (Atauri et al. 2010). Noticeable advances in leaf unfolding, flowering, and fruiting have been observed in recent decades for fruit trees in the western Mediterranean, which have been accompanied by an increase of over 2 weeks in the length of the growing season and less spatial variability in the timing of phenological stages (Gordo and Sanz 2009). Advanced timing of springtime phenophases for apple and sweet cherry trees in Germany is correlated with an earlier beginning of the growing season (Chmielewski et al. 2004), while cherry trees in Switzerland have displayed an earlier appearance of springtime phenological phases, and although less pronounced, later phases in autumn (Defila and Clot 2001). Warming trends were also associated with observed advances in spring phenology ranging from 2 to 8 days for the period 1965–2001 for apples and grapes in the Northeastern United States (Wolfe et al. 2005). As a consequence of warming, suitable climate conditions for apple production have moved inland and northward in Finland, as the risk of extreme low temperatures decreased from ~1980 to 2000 (Kaukoranta et al. 2010). Several studies indicate that damage accruing from spring frost is decreasing. For example, there has been a general reduction in the risk of spring frost in recent decades for apples in Trentino, Italy (Eccel et al. 2009). In the western United States, both late spring and early fall freeze events are becoming less common, and the area is now more conducive to the ripening of wine grapes (Jones 2005).

Negative consequences of observed warming have also been reported. All major wine grape growing regions across the world have experienced warming during the growing season, but 12 out of the 27 regions experienced a decline in production associated with optimum growing season temperatures above vintage ratings (Jones et al. 2005). Ramos et al. (2008) reported that a warming of 1.0–2.2 °C during the growing season led to an increase in heat accumulation for wine grapes in Spain and resulted in a 6–14% increase in water demand.

Winter damage is another factor that may affect the productivity of perennial trees. Studies of grapes, peach, apricot, sweet cherry, pear, and apples in the Okanagan Valley of British Columbia reveal that poor fruit production was due to winter freeze events caused by more frequent Arctic airflow in November–December than in the past (Quamme et al. 2010; Caprio and Quamme 1999, 2006). Modeling experiments conducted by Marshall et al. (2003, 2004) suggest that land use change might have exacerbated freeze risk in the citrus production regions of south Florida, as minimum temperatures were warmer, and below freezing temperatures persisted for a shorter period, for the model simulations that employed pre-1900s land cover compared to those with near present day land cover.

Analyses of the impact of historical climate trends on the break of dormancy for grapes, kiwi, peach, and sweet cherry in California indicate that most locations experienced a significant negative trend in winter chill hours (Baldocchi and Wong 2006). In a later study, trends in winter chill in the Central Valley of California for fruits and nuts were observed to range between −50 and −260 chilling hours per decade (Baldocchi and Wong 2008). Hennessy and Clayton-Greene (1995) analyzed a number of high-chill fruits in Australia (e.g., plum, apple, pear, cherry, peach, and apricot) and demonstrated that warming causes greater reduction in chilling at sites with a higher mean temperature and a wider diurnal temperature range.

Although not as widely studied, precipitation variability also plays a role in the productivity of perennial fruit trees. For example, a slight decrease in precipitation during the bloom to veraison period resulted in plant water stress in a study involving wine grapes in Spain (Ramos et al. 2008). In contrast, Zavalloni et al. (2008) found that the amount of precipitation preceding the end of the previous growing season helped to explain historical yield variations of sour cherries in Michigan (USA).

2.04.6 CO_2 Fertilization

A modest number of studies have investigated the potential impacts of CO_2 enrichment on crop growth and development. In a relatively early study, photosynthesis rates were found to increase when sour orange trees were exposed to elevated CO_2 concentrations (Idso et al. 1991). More recently, Allen and Vu (2009) found that young sweet orange trees grown in greenhouses displayed increased photosynthetic rates, but decreased leaf development and fine root biomass, with elevated CO_2 concentrations. A 2-year FACE (Free Air CO_2 Enrichment) experiment for wine grapes suggested that elevated CO_2 concentrations have an early season effect on fruit dry weight and concentrations of tartaric acid and total sugar, but by the time the grapes reach maturity there was little evidence of any impact of CO_2 fertilization on grape quality (Bindi et al. 2001). In terms of yield, a 3-year open top chamber study found grape yields increased under elevated CO_2 concentrations in the Mediterranean (Moutinho-Pereira et al. 2009). These short-term experiments suggest a complex relationship between CO_2 fertilization and perennial crop growth and development, although the impacts of CO_2 fertilization over the entire lifetime of an orchard are still largely unknown. Furthermore, differences in the impacts of CO_2 fertilization by species and cultivar are not well documented.

2.04.7 Potential Impacts of Climate Change on Perennial Crops

In addition to CO_2 fertilization, future changes in temperature, precipitation, humidity, wind, thunderstorm and hail frequency, and other climate variables could have a substantial impact on perennial crop production. The majority of studies that have investigated potential future impacts for perennial crops have applied a 'feed-forward' assessment strategy, as illustrated in Figure 4. Commonly, climate scenarios (also referred to as climate projections) were substituted in place of observations as input to chill, phenology, and yield models or to calculate heat accumulation, agro-climatic indices, water budgets, or pest and disease frequency. A climate scenario is simply an internally, consistent, and plausible future state (Carter et al. 1996). A climate scenario should be carefully distinguished from a 'prediction' or 'forecast,' as it involves numerous assumptions that may or may not be realized (Mearns et al. 2001). Furthermore, climate scenarios only provide a subset of possible future climate conditions (Jones 2000). For the most part, the climate scenarios that have been used for climate assessments of perennial crops were obtained by 'downscaling' coarse-scale output from global climate models to the local or regional scale. In the discussion below,

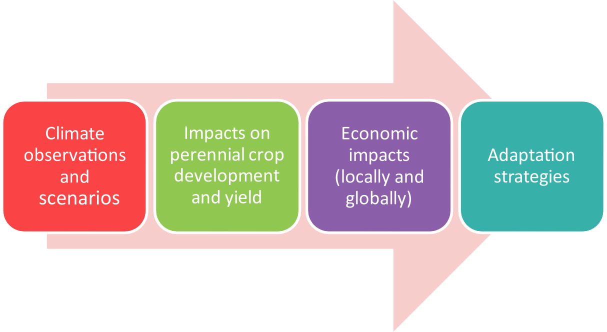
Climate observations and scenarios
Impacts on perennial crop development and yield
Economic impacts (locally and globally)
Adaptation strategies

Figure 4 An idealized feed-forward approach to the investigation of plausible impacts of climate on perennial crops. The vast majority of previous impact assessments have included only the first two steps shown in the figure. Potential economic impacts and adaptation strategies are infrequently addressed and represent a substantial gap in the understanding of climate impacts on perennial crops.

we focus on potential future impacts on perennial crop development and yield. Ideally, a feed-forward approach also includes an evaluation of potential economic impacts and adaptation strategies (the third and fourth steps shown in **Figure 4**), although only a few previous studies of climate change impacts on perennial crops have included an economic component and little research has been conducted on future adaptation options.

Some perennial crops, including apples, could cope better with cold winter temperatures if warmer temperatures linger later into the autumn (Rochette et al. 2004) and the frequency of extreme cold events decreases (Baraer et al. 2010). Consequently, since bud hardening is in part a function of a photoperiod, cold temperatures might not occur until after trees and vines are sufficiently protected by fall hardening (Rochette et al. 2004; Jones 2005). However, despite such an increase in cold hardiness, the risk of winterkill could increase, as suggested by impact analyses for various tree fruits and grapes in eastern Canada (Rochette et al. 2004) and apple production in Finland (Kaukoranta et al. 2010). If there are greater fluctuations in winter temperatures, warm spells might cause a break in dormancy and leave trees at a higher risk of damage by subsequent extreme cold temperatures.

Chilling hours would be reduced with warmer winters, and chilling requirements might not be met as quickly as they have been in the past. Fulfillment of chilling hour requirements has been identified as a potential problem for grape production in Australia (Webb et al. 2007), apple production in Britain (Cannell and Smith 1986), and the production of various fruits in southern Australia (Hennessy and Clayton-Greene 1995) and the Central Valley of California (Baldocchi and Wong 2008). However, one of the greatest concerns for perennial crops is the possibility for warmer temperatures in late winter and early spring. Bud break is strongly related to heat accumulation, and with warmer temperatures in late winter and early spring many fruit and nut trees might reach bud break earlier than they do at present (Cannell and Smith 1986; Rochette et al. 2004; Webb et al. 2007; Kaukoranta et al. 2010; Blümel and Chmielewski 2011). With earlier bud break and flowering, tree fruit may have an increased risk of frost damage as is suggested by analyses of apple production in Finland (Kaukoranta et al. 2010), and apple, pear, peach, apricot, sweet cherry, plum, and grape production in eastern Canada (Rochette et al. 2004). Others have suggested that plants may physiologically acclimate to a warmer climate and thus reduce the plant's risk of frost damage (Eccel et al. 2009).

Higher temperatures during the warmest part of the growing season also might have substantial impacts on perennial crop production. Impact studies investigating grape and wine production in the western United States (Jones 2005), Italy (Bindi et al. 1996), and across the globe (Jones et al. 2005) suggest that temperatures could become too warm for optimal fruit growth or that wine quality may be affected. Warmer temperatures have also been found to speed the phenology of perennial crops, sometimes resulting in earlier harvest dates (Webb et al. 2007).

Regional variations in potential climate impacts also occur and will continue. For example, warmer temperatures could, depending on location and current conditions, negatively or positively impact wine quality (Jones et al. 2005). In more northerly production areas, citrus crops might benefit from warmer temperatures in winter because the risk of frost decreases, but more southerly production areas may see a decrease in productivity due to temperatures that are warmer than optimal (Rosenzweig et al. 1996; Tubiello et al. 2002). Additionally, if the spatial patterns of temperature and precipitation change, it is possible that the distribution of the varieties that are grown would shift; several authors have already indicated that this is a distinct possibility for wine grape production in some regions (Kenny and Harrison 1992; Hall and Jones 2008).

A limited number of studies have investigated the sensitivity of future changes in yield to climatic conditions. Increased temperatures might increase wine production in Portugal, although decreases in rainfall may limit production in some regions (Gouveia et al. 2011; Santos et al. 2011). Some locations may be relatively insensitive to changes in local and regional climatic conditions with only very small changes in yield, as is suggested by an analysis of the productivity of grapes, oranges, and avocados in California (Lobell et al. 2006). Similarly, an assessment conducted by Stöckle et al. (2010) suggests that apple production in eastern Washington might only decrease slightly with perturbed climatic conditions.

Warmer temperatures might also have indirect impacts on perennial crop production in the form of diseases and pests. With longer and warmer growing seasons, it is possible that the number of insect generations during a given season would increase and that the timing of insect infestations might differ significantly from what they are presently, as suggested for apple codling moth in the Great Lakes region of North American (Winkler et al. 2002). An increase in wet weather during the blooming period might reduce the effectiveness of pollination in plants and also cause increased problems with bacterial and fungal diseases (Ladányi et al. 2010).

2.04.8 Adaptation Options

Climate significantly influences perennial crop development, quality, and yield, and this clearly points to the need to consider options for adapting to a spectrum of future climate conditions. Numerous options have been proposed for adapting to climate-related risk. For example, low chill cultivars and dormancy-breaking chemicals are two possible adaptation options for areas where chilling requirements may not be met in the future (Luedeling et al. 2009). Cold-resistant cultivars and frost protection (e.g., sprinklers) are potential adaptation strategies where springtime freeze hazard may increase, and breeding for heat resistance cultivars is one strategy for locations where warmer temperatures might occur during the growing season. Irrigation may be a feasible adaptation strategy for some areas where water stress increases, and hail nets are options if thunderstorms frequency increase (**Figure 5**). More generically, management practices that influence an orchard's microclimate (e.g., planting density and pruning; Luedeling et al. 2009) can help adapt to a number of climate-related risks. A more extreme adaptation option is a switch in land use, either to another crop type or to a nonagricultural use. Although most of the studies that we reviewed acknowledged

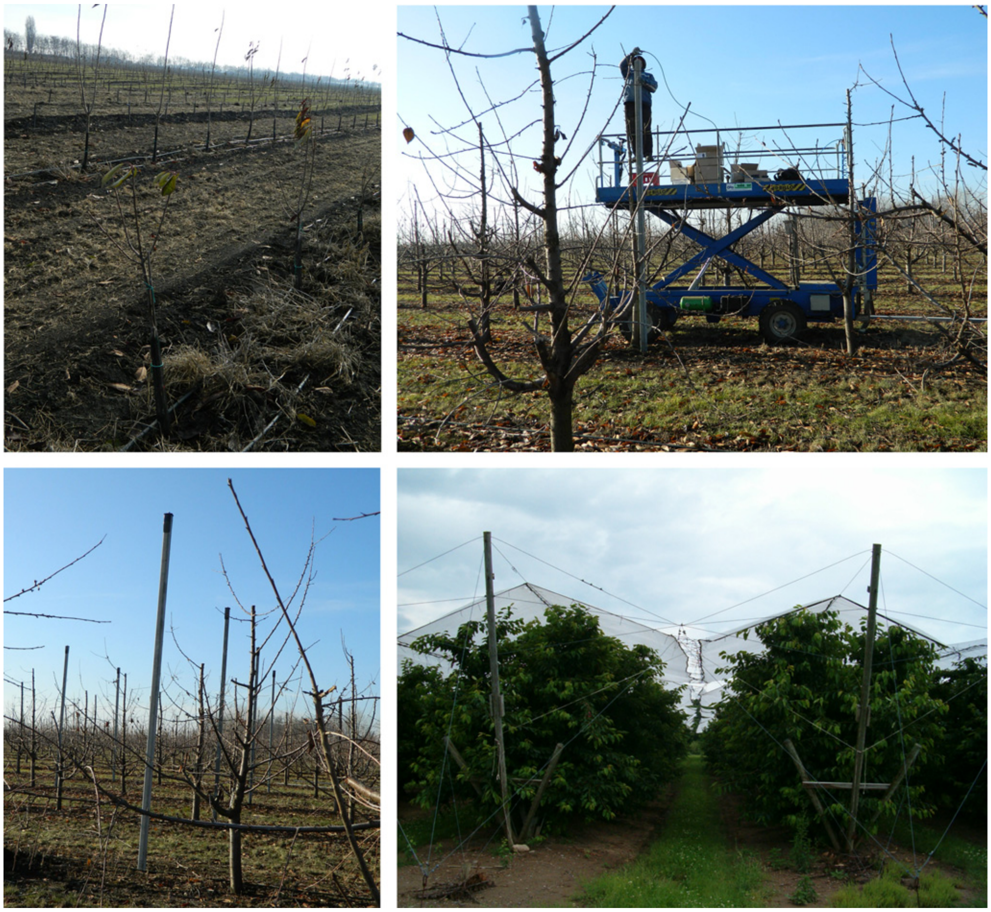

Figure 5 Example adaptation options for perennial crops. Upper left: An irrigated sour cherry orchard in Hungary. Upper right: Workers installing supports for hail nets in a sour cherry orchard in Hungary. Lower left: Hungarian orchard with both irrigation and supports for hail nets. Lower right: Deployed hail nets in a sweet cherry orchard at Cornell University (USA). Photo credit: Dr. Geza Bujdosó, Research Institute for Fruit Growing and Ornamentals, Budapest, Hungary.

that adaptation options need to be considered, none systematically evaluated the feasibility and economic consequences of alternative adaptation options. In other words, previous research on future perennial crop production has stopped well short of a formal adaptation assessment.

2.04.9 Next Steps

The majority of the research discussed above focused on a location or a region. Recently, Winkler et al. (2010) highlighted the need for assessment strategies for international market systems that go beyond the local–regional focus of traditional climate assessments but that incorporate more detail than the broad, but often overly simplistic, approach of many cross-sectoral integrated assessments (e.g., Nordhaus 1994). Using the international sour cherry industry as an example, Winkler et al. (2010) called for an 'expanded impact assessment' that treats perennial crop systems as an international rather than local industry and that considers variations in climate-related risk between production regions. They further argued that temporal dynamics need to be included in the assessment process including changes in patterns of international trade, consumption, and production along with evolving adaptation strategies by industry stakeholder groups. To do this requires advances in crop modeling, preferably the development of process models that can be applied to multiple species and cultivars, improved availability and international exchange of climate and phenological observations for model development, the modification of currently available trade models for use in climate applications, improved models of individual decision making, and methods for evaluating adaptation options. Additionally, strategies need to be improved for communicating the 'meta-uncertainty' (Winkler et al. 2010) of the assessment outcomes to industry stakeholders. All these present considerable challenges but challenges that are more likely to be addressed with greater involvement of industry stakeholders throughout the assessment process.

2.04.10 Summary

Climate-related risk is large for perennial crops given their exposure to fluctuating weather conditions throughout the year. Key vulnerabilities include the fulfillment of winter chill requirements, springtime freeze risk, climate-related constraints on pollination, heat stress, and disease and insect pest pressure. A myriad of methods have been employed to evaluate the past and future climate vulnerability of perennial crops. Temporal and spatial changes in the frequency and timing of critical thresholds and heat accumulation have been particularly popular approaches to assessing past trends and potential future risk. Agro-climatic indices have been widely applied to evaluate the spatial distribution of suitable production regions. Modeling efforts remain largely empirical, although quasimechanistic phenological models exist in addition to empirical models. Impact assessments for perennial crops are handicapped by the lack of process-based crop development and yield models.

Analyses of the influence of historical climate variability on perennial crops, while varying by crop type and location, suggest earlier dates of bloom and other phenological stages and, for some locations, a reduction in spring and early fall freeze risk. Fruit quality appears to have suffered in some growing regions, and winter injury has increased in high latitude growing regions. Additionally, a negative trend in chilling hours has been observed for a number of species and production regions. Plausible future impacts under a warmer climate include fewer chilling hours, earlier bud break and bloom, changes in fruit quality as temperatures surpass crop-specific optimal temperatures, and reduced frequency of winter, but not necessarily springtime, cold temperature damage. Several analyses suggest that pest and disease risk could increase in the future, with an increase in the number of insect generations per season and the frequency of bacterial and fungal diseases.

Climate assessments for perennial crops need to move beyond the local and regional scales, and recognize that perennial crops constitute an international market system with multiple production regions with varying climate-related risk and that market systems respond to changes in demand, as well as changes in supply. Additionally, grower decision making and adaptation options need to be more formally addressed. Climate assessments for perennial crops will benefit from greater stakeholder input.

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Oregon Climate Change Research Institute: http://occri.net/climate-science.

Pileus Project website: http://www.pileus.msu.edu/.

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2.05 Role of Engineering Plants for Abiotic Stresses

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Glossary

Association mapping Method for detecting genetic loci that influence phenotypic traits based on linkage relationships in collections of genetic materials.

Bacillus subtilis Common bacteria found in the soil, air, water, and decomposing plant tissue. Laboratory strains are used for transformation of genes into plant tissue.

Chaperone (Molecular) A group of diverse proteins supervising in the correct folding, assembly of polypeptides, protein formation, and protein complexes.

Cytokinin Plant hormone synthesized by the roots, where it is translocated upward into the plant shoots. It is involved in promoting cell division, tissue growth, and budding.

Ethylene Gaseous, organic hormone produced by plants involved in fruit ripening, seed germination, senescence, and other elements of plant development.

Genomic selection A form of genetic selection that uses DNA markers covering the genome to detect and select for quantitative trait loci (QTL) influencing key traits.

Stacking The integration of multiple genetic traits into a single genetic background.

2.05.1 Plant Breeding: A Science for Change

The Neolithic Revolution marks the extended transition of human lifestyles from hunting and gathering to agriculture. As the cultivation of plants became more prevalent, primitive societies around the world began selecting plant types from their respective geographical regions and planting the seeds of the most productive or attractive types in the next season (Fuller et al. 2011). This selection pressure resulted in a shift in plant types, a "domestication syndrome" that favored plants that were easily harvested and stored for processing and consumption at a later date (Allard 1999).

Although plant selection by farmers and hobbyists occurred over thousands of years, it is only recently that plant breeding was recognized as a science. The science of plant breeding involves making deliberate crosses between individuals with complementary attributes and applying genetic principles to the progeny to develop new cultivars with desired characteristics. Perhaps the best known example demonstrating the power of plant breeding for engineering new plant types with yield enhancing characteristics is highlighted by the successes of Dr Norman Borlaug. Dr Borlaug began his innovative research at the International Maize and Wheat Improvement Center (CIMMYT) in Mexico to develop wheat varieties with multiple "famine resistance" traits, including semidwarfism, yield stability, broad adaptability, and tolerance to abiotic and biotic stresses. Dr Borlaug's vision for crop improvement led to the development of new wheat cultivars that played a key role in achieving food security for many developing countries in the 1960s and 1970s, sparking what is now called the Green Revolution (Khush 2001). Plant breeding successes in wheat were translated to rice and resulted in even more widespread impacts of crop improvement on global food security. Although years of continuous research were required to accumulate various crop adaptation traits into elite cultivars, the ultimate success of this effort resulted in Dr Borlaug's recognition with the Nobel Peace Prize in 1970 to commemorate his contributions to world peace through increasing and stabilizing the global food supply.

Plant breeding strategies to engineer plants for greater yield potential are well established. Global crop production has risen steadily since the Green Revolution (Figure 1). However, these advances in crop productivity may not be sufficient to meet future needs given a projected 39% increase in global population by 2050 (Population Reference Bureau). The trend is also flattening and large uncertainty exists regarding different stresses that can reduce the yield further in the future. This problem is exacerbated even further by the emerging threats listed in previous chapters. These challenges call for another Green Revolution to engineer new climate resilient crops.

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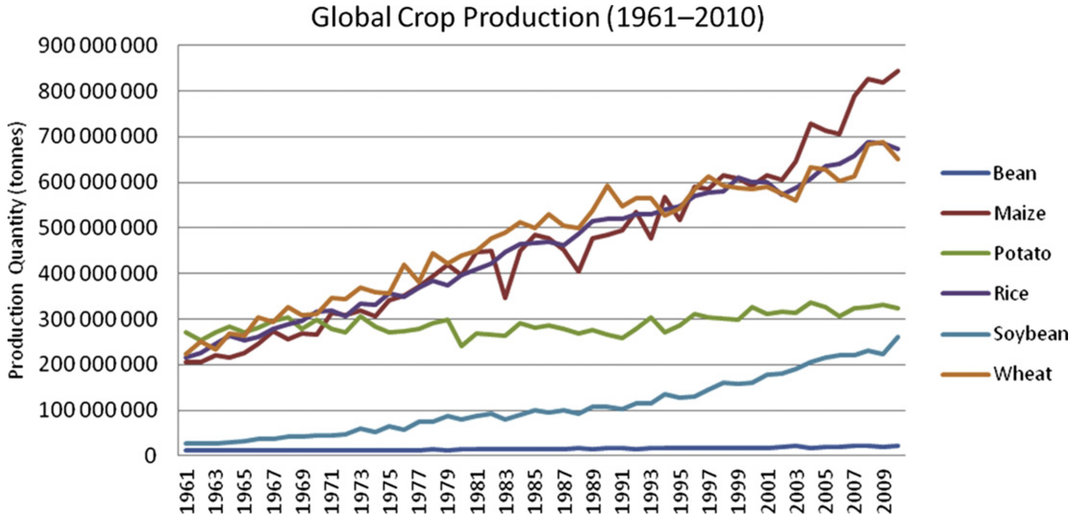

Figure 1 Global production of key crops from 1961 to 2010. Source: FAOSTAT (http://faostat.fao.org).

2.05.2 Climatic Impacts on Crops

Agriculture and our global capacity for food production are highly vulnerable to the weather and climate patterns, especially the effects of rising or variable temperatures and drought. Plant yields are also expected to be vulnerable to inundation and flooding of coastal farmlands, as well as increase in soil salinity in various locations (Rignot et al. 2003; Saleemul et al. 2004). Climate variability and elevated daytime and nighttime temperatures and diurnal temperature ranges may even threaten soil nutrients such as nitrogen availability in some parts of the world through increased losses of nitrogen under elevated soil temperatures (Houghton et al. 2001; Parry et al. 2007; Smith et al. 2007).

Biotic stresses, including plant pathogens and insects, and their interaction with abiotic stresses present further challenges to global food production and security. Although not discussed in this perspective paper, the effects and interactions of biotic stresses and climate have been thoroughly reviewed by Atkinson and Urwin (2012), Luck et al. (2011), and Newton et al. (2011).

2.05.3 Advancements in Engineering Plants for Tolerance to Abiotic Stresses

Plant breeders are confronted with the task of creating new crop cultivars that can tolerate a wide range of environmental stresses. In the subsequent sections, we report on technological advancements in genetic technologies being developed to enhance crop performance under abiotic stresses including drought, heat, salinity, and flooding. A listing of new traits and technologies are summarized in Table 1.

2.05.3.1 Increased Tolerance to Drought

The agricultural enterprise is aware that the occurrence and severity of drought conditions will likely increase as temperatures rise. Drought is defined by the World Meteorological Organization as "a deficit of rainfall in respect to the long term mean" affecting a large area for one or several seasons or years (Hounam et al. 1975). Farmers and plant breeders are exploring opportunities to address this challenge using natural genetic variation as well as transgenic breeding methods and biotechnology.

Maize breeders commercially have been working for a number of years to increase the intrinsic levels of drought tolerance in hybrid maize. The strategy is to use forms of genomic selection and association mapping to identify native genes of maize that contribute to improved hybrid performance under drought. For example, researchers at Pioneer Hi-Bred are using an Advanced Yield Technology system to identify and stack multiple drought tolerance-related genes into elite hybrids. New hybrid cultivars are being commercialized under the brandname Optimum®AQUAmax™. Recent experiments conducted in Nebraska, California, Texas, Colorado, Kansas, and Oklahoma showed that AQUAmax™ hybrids exhibited 5% higher yields under water-limited situations compared with other commercial checks. This technology was commercially released in 2011 and targets dry land corn production systems in the Western Corn Belt of the United States (Dupont 2012; Pioneer 2012). Syngenta is using a similar gene stacking system called Gene Blueprinting Technology. Using this selection strategy, Syngenta has incorporated 12 genes involved in multiple drought tolerance pathways into elite hybrid backgrounds. Syngenta estimates that these hybrids have a 15% yield advantage in drought environments. These hybrids are being marketed under the brand name Agrisure Artesian™ Technology. This technology was commercialized in 2011 and is targeted for production environments in the Western Corn Belt of the United States (McCabe 2010; Syngenta Inc 2012).

Genetic engineering to enhance drought tolerance using transgenes is also being investigated. Monsanto Company in collaboration with BASF identified a cold shock protein B (*CspB*) from a soil bacterium *Bacillus subtilis* that provides enhanced hybrid performance under drought conditions. *CspB* is expressed under drought stress and acts as a RNA chaperone that aids in the unfolding of misfolded secondary RNA structures, thus allowing and facilitating RNA translation (Health Canada 2012; Reeves et al. 2009; Graumann and Marahiel

Table 1 Examples of technologies for engineering crop plants for abiotic stress tolerance

Abiotic stress	*Crop*	*Developing organization*	*Breeding method*	*Technology*	*Growing region*
Drought	Maize	Pioneer Hi-Bred	Conventional	Optimum® AQUAmax™	United States
	Maize	Syngenta	Conventional	Agrisure Artesian™ Technology	United States
	Maize	Monsanto Company/BASF	Transgenic	First-generation drought-tolerant corn (*CspB*[a])	United States
	Maize	Monsanto Company	Transgenic	Second-generation drought-tolerant corn	United States
	Maize	WEMA[b]	Transgenic + Conventional	*CspB* + native maize genes	African continent
Flooding/ submergence	Rice	IRRI[c]	Conventional	*Sub1A-1*	Philippines, India, and Bangladesh
Salinity	Rice	IRRI	Conventional	Saltol QTL	West Africa and Bangladesh
Nitrogen use efficiency	Maize	Monsanto Company/BASF	Transgenic	Nitrogen-utilization corn	United States
	Maize	Pioneer Hi-Bred	Conventional	Native maize genes	United States
	Rice/canola	Arcadia Biosciences	Transgenic	Alanine aminotransferase	Unknown
Heat	Wheat/maize	CIMMYT[d]/IRRI	Conventional	Native genes	Central America/Asia

[a] Cold Shock Protein B.
[b] WEMA – Water Efficient Maize for Africa (http://www.aatf-africa.org/wema).
[c] IRRI – International Rice Research Institute (http://www.irri.org).
[d] CIMMYT – International Maize and Wheat Improvement Center (www.cimmyt.org).

1998). Monsanto is planning a limited release of *CspB* lines under the brand name First-Generation Drought-Tolerant Corn in the near future. Another technology called Second-Generation Drought-Tolerant Corn is in Phase 2 development within the Monsanto Pipeline and is designed to further enhance the performance of corn under drought stress (Monsanto Company 2012a). *CspB* technology is not limited to use in the United States. The Water Efficient Maize for Africa (WEMA) program is combining plant breeding for drought tolerance with the *CspB* transgene. Hybrid maize varieties that combine these technologies currently are being tested in drought-prone locations across Africa (Open Forum on Agricultural Biotechnology in Africa 2012). Although still very new, these genetic engineering approaches by Monsanto and other companies represent promising new strategies for engineering crop plants for tolerance to drought conditions.

2.05.3.2 Tolerance to Flooding and Submergence

With the increased potential for heavier rainfall and hydrological extremes, agricultural areas are susceptible to flooding and ponding. Plant breeders are identifying and developing genetic technologies to enhance crop productivity under these conditions as well (King 2004).

The best examples of success in breeding for crop tolerance to flooding are found in rice. Most rice cultivars cannot tolerate flooding for more than 1 week (International Rice Research Institute 2012). However, breeders at the International Rice Research Institute (IRRI) identified a class of ethylene-response-factor-like genes that contribute to flooding tolerance in an Indian rice variety. Three genes, *Sub1A*, *Sub1B*, and *Sub1C*, were found to contribute to flooding tolerance. Of these genes, *Sub1A* was the most important factor contributing to submergence tolerance. Physiological studies showed that rice varieties with *Sub1A-1* overproduce the plant hormone ethylene when submerged. Ethylene accumulation delays cytokine-mediated senescence and promotes dormancy during submergence. Rice varieties containing *Sub1A-1* have exhibited a 1–3-ton yield advantage compared with controls following a 10–15-day submergence period. Several important varieties with submergence tolerance have been released, including *Swarna Sub1* in India, *Samba Mahsuri* in Bangladesh, and *IR64-Sub1* in the Philippines (Kenong et al. 2006; International Rice Research Institute 2012; Jung et al. 2010).

2.05.3.3 Salinity Tolerance

Millions of hectares of land in Africa and Asia are characterized as having highly saline soils that are not suitable for agricultural production (Kundzewicz et al. 2008; Sallemul et al. 2004). To address these problems, plant breeders are developing crop varieties with increased tolerance to saline soils (International Rice Research Institute 2012; Thomson et al. 2010). The problem of saline soils is common in many rice-producing areas. Researchers at the IRRI were among the first to discover regions of the rice genome associated with increased salt tolerance. These regions of the genome are classified as *Saltol*. Unlike *Sub1A*, a single gene controlling tolerance to submergence, multiple *Saltol* loci are required to confer salt tolerance. Although polygenic inheritance complicates the engineering of rice for salt tolerance, recent plant breeding efforts have generated rice varieties that are able to cope with salt stresses at the seedling and reproductive growth stages. Furthermore, salt tolerance combined with *Sub1A* for submergence tolerance has been shown to be a powerful technology for developing varieties of rice for flood-prone, saline soils. To date, more than 100 salinity-tolerant rice varieties have been developed for rice production in salt-contaminated regions around the world (International Rice Research Institute 2012).

2.05.3.4 Nitrogen Use Efficiency

Nitrogen fertility management and availability in the soil may be negatively impacted by climate variability as temperatures rise. Environments with soil surface temperatures near or above 40 °C exhibit greater release of soil nitrogen through volatilization and thus leave less nitrogen for plant assimilation (McCalley and Sparks 2009). To address these issues, plant breeders are faced with the challenge of developing crops with greater nitrogen use efficiency (NUE).

Plant breeding to improve NUE is still in early stages of development, but some advancements have been made in this area. The Monsanto Company and BASF are examining biochemical and physiological mechanisms that might be engineered to improve nitrogen use, including enhanced nitrogen uptake and transport, improved nitrogen assimilation, enhanced protein synthesis, improved photosynthesis, improved general stress response, and pathway regulation. However, the genetic mechanisms for enhancing these traits are still poorly understood (Moose and Below 2009; Monsanto Company 2012b). Pioneer Hi-Bred also is conducting research to examine the development of nitrogen use-efficient hybrids with anticipated release of adapted cultivars later this decade. Arcadia Biosciences has developed a transgenic technology for improving NUE based on an alanine aminotransferase (*AlaAT*) gene from barley (*Hordeum vulgare*) licensed from the University of Alberta. The gene has been transformed into rice and canola and was shown to catalyze a reversible transamination reaction in the nitrogen assimilation pathway. Preliminary results from testing show promise for this technology (Arcadia Biosciences 2012; Good et al. 2007).

2.05.3.5 Tolerance to Elevated Daytime and Nighttime Temperatures

Drought and heat stresses often occur at the same time because of the integrated nature of these stresses in drought environments. However, drought is defined as a deficit of rainfall, whereas heat stress is defined as an increase in temperature beyond a threshold level for a period of time sufficient to cause irreversible damage to plant growth and development (Wahid et al. 2005). Plant breeding for heat-stress tolerance in crop plants has lagged behind other abiotic stress tolerance research. Investigations into the genetic mechanisms influencing heat stress responses are underway, but few heat-tolerant cultivars are known. In maize, CIMMYT is conducting a program to screen for genetic tolerance to heat stresses. An extensive screen of lines developed for drought-prone environments in Latin America and Africa indicated that very few of these lines combine heat and drought tolerance traits. Heat and drought stress tolerance were poorly correlated, suggesting that heat and drought tolerance are controlled by different genetic mechanisms. As genetic sources of high-temperature tolerance are identified, it is hoped that inheritance studies will reveal a genetic architecture that can be manipulated to enhance crop productivity in a range of stressful environments (Zaidi and Cairns 2011).

2.05.4 Challenges of Breeding for Climate Variability

Climate effects and associated environmental vulnerabilities appear in multiple forms. Examples of multiple environmental stresses include excess heat, flooding, drought, and increased salinity of soils. Increased frequency of these stresses will negatively affect crop yields beyond the impacts of changes in mean temperature and precipitation and increase the probability that crop production in future environments will be challenged by multiple and variable stresses from year to year. Agriculture will not have the luxury of engineering future crop varieties with tolerances to individual abiotic stress factors associated with climatic factors. Plant breeders are faced with the challenge of integrating, or ‘stacking,’ multiple abiotic stress tolerance traits or factors into each new cultivar to provide tolerance to a broad spectrum of adverse climate conditions. This will be challenging because efforts to stack multiple genes into a single elite cultivar require both the time for the necessary breeding cycles as well as knowledge and understanding of how traits interact and can be combined to maximize productivity. Plant researchers and breeders have made considerable gains in our understanding of these traits, but greater research investments are needed to make progress in understanding the genetic resources, mechanisms, and pathways needed to engineer and adapt crop plants for the range of climate conditions they could face in the coming decades.

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2.06 Climate Vulnerabilities and Wheat Production

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Glossary

CIMMYT	International Maize and Wheat Improvement Center.
EPIC	Environmental Policy Integrated Climate.
FACE	Free-Air CO_2 Enrichment.
GCM	Global Circulation Models.
IPCC	The Intergovernmental Panel on Climate Change.

2.06.1 Introduction

Wheat is a major cereal crop in the world and shares about 21% of the global food production. Based on the average data from 2007 to 2009, the global wheat area is 221.7 million ha, with average yield of 2977 kg ha^{-1}, and production of 660 million tonnes. It is a major source of energy in human diet because its protein content is higher than almost all other cereals. It is the most widespread cereal in terms of planting area. Bread wheat (*Triticum aestivum*) accounts for more than 90% of global production and it is grown on a substantial scale (over 100 000 ha) in more than 70 countries on 5 continents. It is mainly used to make bread including steamed bread, noodles, cookies, cakes, and breakfast cereals. Wheat can be classified as winter and spring type, based on the requirement of vernalization. Spring and winter bread wheats share around 70 and 30%, respectively. Durum wheat (*Triticum durum*) accounts for about 5% of global wheat production and is produced mainly in North Africa and Western Asia (35%), North America (35%), and EU (30%). Most durum wheat is spring type, and it is used to produce semolina, pasta, and cracked wheat products such as couscous or bulgur. About 66% of global wheat production is utilized for food, and the remaining 34% for feed and other purpose. Demand of wheat for human and feed consumption in developing countries in 2020 is expected to increase at 1.6 and 2.6% per year, respectively. The global average wheat yield will have to increase during the next 25 years from 2.6 to 3.5 t ha^{-1} (Dixon et al. 2009). Other reports indicate that demand for wheat in developing countries is projected to increase by 60% by 2050 (Rosegrant and Agcaoili 2010). Therefore, increasing wheat productivity is crucial for food and feed security, particularly in the developing countries.

Climate is a major issue in agricultural systems including cereal production. For example, after a 10-year drought, Australia experienced catastrophic floods during fall 2010 and winter 2011, leading to loss of an estimated $6 billion in grain harvest. Estimates of the possible impacts of changes in climate on crop production are inconclusive and model-dependent (Tubiello et al. 2000).

Increased temperatures, major alternations in precipitation patterns, and atmospheric CO_2 concentration, are most important for wheat production. Since 1980, global wheat and maize production have declined by 5.5 and 3.8%, respectively, but with less of a change in rice and soybean **Table 1**. Regional

http://dx.doi.org/10.1016/B978-0-12-384703-4.00235-5

Table 1 Median estimates of global impacts of temperature and precipitation trends on yield, 1980–2008

Crop	*Impact of temperature (%)*	*Impact of precipitation (%)*	*Subtotal*	*Impact of CO_2 (%)*	*Total*
Maize	−3.1	−0.7	−3.8	0.0	−3.8
Rice	0.1	−0.2	−0.1	3.0	2.9
Wheat	−4.9	−0.6	−5.5	3.0	−2.5
Soybean	−0.8	−0.9	−1.7	3.0	1.3

Data source: Lobell, D. B., W. Schlenker, and J. Costa-Roberts, 2011: Climate trends and global crop production since 1980. *Science*, **5** May 2011/ 10.1126/science.1204531

differences are also observed in Table 2 (Lobell et al. 2011). Therefore, much more attention must be given to understanding the effects of climate on wheat production, so adaptive measures can be taken to ensure global wheat supply in the future. The objective of this chapter is to summarize the impacts of climate on wheat production globally, with a focus on China and India, the first and second largest wheat producers, respectively.

2.06.2 Climate across Wheat Megaenvironments

2.06.2.1 Impact of Increasing Temperature on Wheat Production

Wheat is generally sensitive to temperature increase, which can hasten crop development and shorten grain filling period thus potentially reducing yield, but actual effects are highly dependent on background ambient temperature, which can be associated with geographic location and wheat type (winter or spring type), stage development, and variety.

Data from Australia and Argentina indicated that time from sowing to maturity was reduced up to 0.3 day $year^{-1}$ and time to flowering accounted for most of the variation in time to maturity; and the duration of the postflowering phase was largely unchanged (Victor and Monzon 2006). For spring wheat in a tropical or subtropical environment such as in the Indo-Ganetic Plains of India, increasing temperature would significantly reduce crop season and decrease yield. For winter and facultative wheats in temperate region such as in the Yellow and Huai Valleys of China, increasing temperature has allowed the delayed planting of wheat, reduction of winter-kill, early development in spring, early heading, and slight advance of maturity, thus positive effects on yield could be expected. However, for both environments, heat shock day (temperature over 30 °C) during grain filling period can severely reduce grain yield, largely owing to the reduction of the grain filling period. Temperature increases could reduce wheat in the developing world by 20–30% (Easterling et al. 2007; Lobell et al. 2008; Rosegrant and Agcaoili 2010). Based on the data from 1980 to 2008, the impact of temperature trends to global wheat production is −4.9%, much higher than that for precipitation (−0.6%), although the assumed impact of CO_2 concentration is also higher (+3.0%) (Lobell et al. 2011). Therefore, rising temperature is the most important factor limiting wheat production.

2.06.2.2 Impact of Change in Precipitation Patterns on Wheat Production

Rainfed agriculture depends heavily on rainfall patterns, and precipitation changes may lead to severe droughts in some places and water logging in others (Lobell et al. 2008). Based on the data from 1980 to 2008, the impact of precipitation for global wheat production is −0.6%, but varied in different countries as presented in Table 2 (Lobell et al. 2011). The impact of reduced water availability on rainfed wheat systems is presented in Section 2.06.2.4. Because of the shortage of water, irrigation for wheat production in northern parts of the Yellow and Huai Valleys in China has been reduced from 4–5 to 2–3 times. Occurrence of continuous droughts in China in 2009 and 2011 has significantly reduced wheat production; during the last few years, severe droughts also occurred in Australia, Russia, and EU countries.

2.06.2.3 Impact of Elevated CO_2 on Wheat Production

Based on the IPCC (2007) report, CO_2 has increased from around 280 ppm in the preindustrial era to around 380 ppm in 2005. Apart from positive radiative forcing and resulting surface warming, increasing CO_2 concentration has the potential to increase plant growth and yield in all environments, primarily caused by increased photosynthesis, with greater benefits for C_3 crops such as wheat. Kimball et al. (2002) reported a 10–20% wheat yield increase at 550 ppm

Table 2 Estimated impact of temperature and precipitation trends from 1980 to 2008 on wheat production in five countries

Country	*Impact of temperature trend (%)*	*Impact of precipitation trend (%)*	*Impact of CO_2 trend (%)*	*Total*
China	−2.2	−0.2	3.0	0.7
India	−3.7	−1.8	3.0	−2.5
United States	0.9	0.0	3.0	3.9
Russia	−13.7	−0.5	3.0	−11.3
France	−5.0	0.6	3.0	−1.4
Global	−4.9	−0.6	3.0	−2.5

Data Source: Lobell, D. B., W. Schlenker, and J. Costa-Roberts, 2011: Climate trends and global crop production since 1980. *Science*, **5** May 2011/ 10.1126/science.1204531.

CO_2 depending on nitrogen and water availability. Based on the review of 50 studies on this subject, Amthor (2001) concluded that elevated CO_2 would have a positive impact on yield, but varying with the availability of water, nutrients, and temperature. Leakey et al. (2009) reviewed the six lessons learned from FACE (Free-Air CO_2 Enrichment) regarding the elevated CO_2 effects on plant carbon, nitrogen, and water relations. Controlled laboratory and field chambers have provided an immense database on plant response to rising CO_2 and more importantly, insight into potential mechanisms of response. FACE, which allows treatment of plants under field conditions at a realistic scale, has provided an important reality check. Overwhelmingly, this has shown that data from laboratory and chamber experiments systematically overestimate the yield of major food crops (Leakey et al. 2009).

2.06.2.4 Impact of Climate across Wheat Megaenvironments

The International Maize and Wheat Improvement Center (CIMMYT) has globally defined 12 wheat megaenvironments involving spring wheat (ME1–ME6), facultative wheat (ME7–ME9), and winter wheat (ME10–ME12). A megaenvironment is defined as a broad, not necessarily contiguous, area, occurring in more than one country and frequently transcontinental, defined by similar biotic and abiotic stresses, cropping system requirements, consumer preferences, and, for convenience, by volume of production (Rajaram et al. 1995). Hodson and White (2009) have given an overall review regarding the impact of plausible climate scenarios on future wheat production although the analysis on winter wheat is relatively weak in comparison with spring wheat; therefore, most of the information presented below is derived from their publication, although recent available information is added as necessary.

As indicated in Table 3, for spring wheat from ME1 to ME5, rising temperature would have a negative effect on yield; however, it would have a positive effect on yield for spring wheat in ME6 and winter wheat from ME10 to ME12. Its effect on facultative wheat from ME7 to ME9 is uncertain although observations from China are generally positive.

Effect of changing precipitation is more complex. Reduced water availability would have a negative effect on yield in irrigated environments and rainfed environments such as in ME1, ME2A, ME4A and ME4B, ME7, ME9, ME10, and ME12, through reduced irrigation or evolving from partial irrigation to rainfall crop production. However, it may have uncertain effects on yield in high rainfall environments such as in ME2B, ME3, ME4C, ME8, and ME11.

2.06.2.5 Impact of Climate on Wheat Diseases and Pests

Changes in atmospheric composition and the rest of the climate system would include temperature, rainfall, and humidity, which would affect the economic importance, geographical distribution, and management of diseases effecting crop production. Climate affects the effectiveness of host plant resistance and pathology fitness because of modified host and pathology, and host–pathology interaction. Wheat scab and wheat stripe rust severity in China and stem rust in the United States have been linked to the El Niño-Southern Oscillation Index (Scherm and Yang 1995). New stem rust pathotype 'Ug99' can pose significant threats to global wheat production (McIntosh and Pretorius 2011). Wheat blast, caused by a fungus *Magnaporthe grisea*, first identified in Brazil in 1985, is an emerging disease in South America. The disease has become a serious threat to wheat production in the tropic and subtropic regions, including Brazil, Argentina, Bolivia, and Paraguay. Climate is the key factor to the disease development, and hot and humid climate favor the development of wheat blast (Kohli et al. 2010).

Models predicting the geographical distribution of host plants and their diseases as a function of climate can serve as a guide to possible future disease prevalence. However, only four diseases of field crops have been studied under realistic field conditions in FACE facilities, and the effects of climate on wheat yellow rust were reported by Chakraborty et al. (2011). The effectiveness of resistance in wheat varieties could change under a changed local and regional climate and/or resistance maybe overcome quickly by new pathotypes. For wheat leaf rust, obligate parasitism is generally inhibited by elevated O_3; infection by facultative pathogens could increase, decrease, or remain unchanged (Tiedemann and Firsching 2000). Under the ambient (380 ppm) and elevated CO_2 (820 ppm) concentrations, there are no interaction between CO_2 concentration and level of resistance, and the effectiveness of partial resistance in variety Janz was not changed (Chakraborty et al. 2011). It is likely that rusts of wheat would be able to adapt to increased temperature as reported for yellow rust in the eastern United States (Markell and Milus 2008). In wheat, the expression of many genes for resistance to leaf rust, stripe rust, and stem rust is influenced by temperature and/or plant development stage. Some resistance may become less effective at high temperature. For example, *Yr18* is known to be temperature mediated and become more effective at higher temperature. Rust reaction of varieties with *Sr15* can change from resistance at 15 °C to nearly fully susceptible at 20 °C. Much more work is needed to understand the performance of partial resistance genes under rising CO_2 and temperature levels. Australia and the United States have increased emphasis on durable resistance based on additive effects of partial resistance genes.

2.06.3 Climate and Wheat Production in China

2.06.3.1 Wheat Ecological Zones

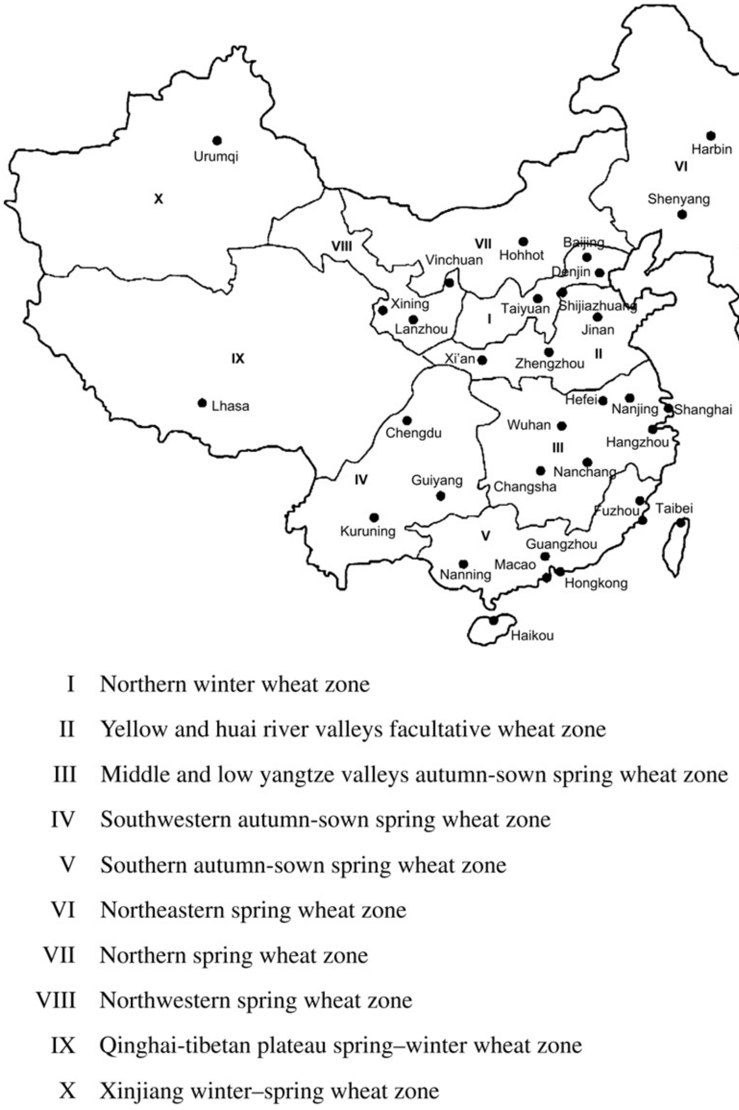
China is the largest wheat producer and consumer in the world. At present, around 23.5 million ha of wheat are harvested annually, with a production of about 110 million tonnes. Chinese wheat area has been divided into 10 major agro-ecological zones as presented in Figure 1, based on wheat types, varietal reactions to temperature, moisture, biotic and abiotic stress, and wheat growing seasons (He et al. 2010). On the basis of sowing dates, autumn-sown wheat accounts for more than 95% of production and acreage. Winter and facultative wheat, sown in the North China Plain (Zone I) and the Yellow and Huai River Valleys (Zone II), contribute around 70% of the production. Autumn-sown, spring habit wheat, planted in both the Middle and Low Yangtze Valleys (III) and the southwestern China (Zone IV), contributed around 25% of production. Spring-sown spring wheat is mostly planted in northeastern and northwestern China (Zones VI, VII, and VIII)

Table 3 Suggested impacts on wheat production in different megaenvironments (MEs) from a set of climate metrics

Mega-environment	*Representative sites*	*Concerns/opportunities*
Spring wheat		
ME1: Favorable, irrigated, low rainfall	Gangetic Valley, India Indus Valley, Pakistan Nile Valley, Egypt Yaqui Valley, Mexico	N – Rising temperature result in large areas evolving to ME5 N – Reduced precipitation in subtropical regions restricts irrigation P – Reduced irrigation due to impact of elevated CO_2 on water use efficiency
ME2A: Highland, summer rain	Kulumsa, Ethiopia	N – Rising temperature result in large areas evolving to ME5
ME2B: Lowland, winter rain	Toluca, Mexico Izmir, Turkey Pregamino, Argentina	N – Reduced precipitation result in areas evolving to ME4 N – Rising temperature result in large areas evolving to ME5 U – Changes in precipitation patterns in areas will have variable effects
ME3: High rainfall, acid soil	Passo Fundo, Brazil Mpika, Zambia	N – Rising temperature result in large areas evolving to ME5 N – Rising temperature result in large areas evolving to ME5
ME4: Low rainfall	See below	N – Rising temperatures exacerbates water deficits, either further reducing yield or making production uneconomical P – Reduced water deficits through impact of elevated CO_2 on water use efficiency
ME4A: Winter rain or Mediterranean type climate	Aleppo, Syria Settat, Morocco	N – Rising temperature result in large areas evolving to ME5 N – Changes in precipitation patterns likely to increase drought risk
ME4B: Winter drought or Southern Cone type rainfall	Marcos Juarez, Argentina	N – Rising temperature result in large areas evolving to ME5 N – Changes in precipitation patterns likely to increase drought risk
ME4C: Stored moisture	Dharwar, India	N – Rising temperature result in large areas evolving to ME5 U – Changes in precipitation patterns in areas will have variable effects
ME5: Warm, humid, or dry	Joydebpur, Bangladesh Encarnacion, Paraguay Kano, Nigeria Wad Medani, Sudan	N – Rising temperature result in large areas becoming unsuitable for wheat N – Increasing biotic stress U – Elevated CO_2 may increase water use efficiency, but the same mechanism implies increased canopy temperature, which likely would exacerbate heat stress
ME6: High latitude (>45 °N or S)	Urumqi, Xinjiang, China Astana, Kazakhstan Harbin, Heilongjiang, China	P – Rising temperatures lengthen growing season and permit marginal areas to become productive P – Reduced risk of winter-kill allows conversion to more productive winter wheat
Facultative wheat		
ME7: Favorable, moderate cold, irrigated	Zhenzhou, Henan, China	U – Reduced cold stress allows growing spring wheat, possible reducing yield potential, but shortening growing season P – Reduced irrigation due to impacts of elevated CO_2 on water use efficiency
ME8: High rainfall (>500 mm), moderate cold	Diyarbakir, Turkey Vernon, Texas	U – Reduced cold stress allows growing spring wheat, possible reducing yield potential, but shortening growing season U – Changes in precipitation patterns in areas will have variable effects P – Reduced water deficit through impact of elevated CO_2 on water use efficiency
Winter wheat		
ME10: Favorable, cold, irrigated	Beijing, China	P – Warmer winters reduced severity of winter-kill, increasing yields N – Warmer spring and summer hasten grain-filling P – Reduced irrigations due to impacts of elevated CO_2 on water use efficiency
ME11: High rainfall, cold	Odessa, Ukraine Krasnodar, Russia	P – Warmer winters reduced severity of winter-kill
ME12: Semi-arid, low rainfall, cold	Ankara, Turkey Manhattan, Kansas	P – Warmer winters reduced severity of winter-kill P – Reduced water deficit through impact of elevated CO_2 on water use efficiency N – Increased insect problems

P = positive impact, N = negative, and U = uncertain.

Data source: Hodson, D., and J. White, 2009: Climate change: what future wheat? *Wheat Facts and Future 2009*, J. Dixon, H. J. Braun, P. Kosina, and J. Crouch, Eds., CIMMYT, 52–61.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Jinan
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Xi'an
Zhengzhou
II
Lhasa
Harbin
VI
Shenyang
Hefei
Nanjing
Shanghai
Chengdu
Wuhan
III
Hangzhou
Nanchang
IV
Guiyang
Changsha
Fuzhou
Taibei
Kuruning
V
Guangzhou
Macao
Nanning
Hongkong
Haikou
I Northern winter wheat zone
II Yellow and huai river valleys facultative wheat zone
III Middle and low yangtze valleys autumn-sown spring wheat zone
IV Southwestern autumn-sown spring wheat zone
V Southern autumn-sown spring wheat zone
VI Northeastern spring wheat zone
VII Northern spring wheat zone
VIII Northwestern spring wheat zone
IX Qinghai-tibetan plateau spring–winter wheat zone
X Xinjiang winter–spring wheat zone

Figure 1 Main wheat production areas in China (indicated by the black dots).

and makes up 5% of the production. More than 70% of Chinese wheat is produced in five provinces: Henan, Shandong, Hebei, Anhui, and Jiangsu. Detailed information on Chinese wheat production was reviewed by He et al. (2010).

2.06.3.2 Wheat Phenology and Cropping System

Annual mean temperature in China showed an increasing trend from 1905 to 2011; the first significant increasing period was from 1930 to 1945, and the second significant increase was observed since 1990. A warming trend was also observed in the major wheat area from 1961 to 2006. The increase of average temperature, maximum temperature, and minimum temperature in the five major wheat provinces (Henan, Shandong, Hebei, Anhui, and Jiangsu) are 0.53–0.75 °C per decade, 0.37–0.70 °C per decade, and 0.58–0.80 °C per decade, respectively (W. Xiong, CAAS, personal communication). In the Yellow and Huai Valleys, which produce around 70% of Chinese wheat, there has been a significant decrease in sunshine hours and radiation since 1961 owing to increase aerosol in the atmosphere, a trend of rising air temperature since 1980s, a trend of decreasing annual precipitation in the northern part, and increasing precipitation in the southeast part of the region. These climatic trends led to a shortened growing period for wheat and an extended growing season for maize under the wheat/maize rotation system (Liu et al. 2010; Tao et al. 2006). However, the impact on wheat phenology and yield was varied because of the different targeting regions and various methods employed. For example, from 1981 to 2000 the maximum and minimum temperatures in Zhengzhou, located in the Yellow and Huai Valleys, in winter (December–February) were significantly increased by 0.95 and 0.92 °C per decade, respectively; whereas in spring (March–May) the minimum temperatures also increased by 0.74 °C per decade, but the maximum temperature did not increase significantly. Wheat planting, anthesis, and maturity dates in Zhengzhou did not occur significantly earlier, and wheat yields did not decrease significantly; however, planting, anthesis, and maturity dates at Tianshui, also located

Table 4 Winter and facultative wheat phenology: grain yield and its components in the warmed at nighttime and unwarmed plots in northern China, from 2007 to 2009

Season	*Location*	*Treatment*	*Sowing date*	*Anthesis date*	*Maturity date*	*Spike* m^{-2}	*Grains spike*$^{-1}$	*Thousand grain weight (g)*	*Grain yield* (*t* ha^{-1})
2007–08	Nanyang	CK	3 Oct 2007	20 April	26 May	554a	29.3b	38.8a	5.73
	Henan Province	NW	3 Oct 2007	16 April	23 May	539a	36.6a	40.0a	7.31
2007–08	Xuzhou,	CK	1 Oct 2007	28 April	4 June	463a	37.4a	38.2b	6.76
	Jiangsu Province	NW	1 Oct 2007	21 April	3 June	448a	42.0a	43.2a	7.64
2007–08	Shijiazhuang	CK	3 Oct 2007	30 April	9 June	453a	36.9b	44.7b	6.59
	Hebei Province	NW	3 Oct 2007	23 April	6 June	441a	39.4a	48.2a	7.53
2008–09	Xuchang,	CK	3 Oct 2008	27 April	4 June	537a	32.7a	36.3b	5.82
	Henan Province	NW	3 Oct 2008	23 April	2 June	524a	34.8a	40.1a	6.15
2008–09	Xuzhou,	CK	4 Oct 2008	29 April	3 June	412a	31.3b	47.7b	5.33
	Jiangsu Province	NW	4 Oct 2008	22 April	2 June	406a	33.2a	50.3a	5.90
2008–09	Shijiazhuang,	CK	3 Oct 2008	1 May	4 June	493a	30.8b	38.3b	6.16
	Hebei Province	NW	3 Oct 2008	23 April	2 June	498a	33.1a	42.4a	7.52

The tested varieties are Yumai 7036 in Nanyang, Yanfu188 in Xuzhou, and Liangxing 99 in Shijiazhuang. CK and NW mean the treatments of unwarmed control and nighttime warming, respectively. Values followed by a different letter are significantly different ($P < 0.05$).
Data source: L. Zhang (2011, unpublished data).

in the Yellow and Huai Valleys, occurred earlier (Tao et al. 2006). Liu et al. (2010) reported the contributions of climate and crop variations to wheat production in three major locations (Luancheng in Hebei province, and Zhengzhou and Nanyang in Henan province). Warming mainly occurred during the vegetative growth stage (preanthesis), whereas there was a cooling trend or no significant change in temperature during the postanthesis stage. If varietal effects were excluded, warming during vegetative stage would lead to a negative reduction in wheat yield. However, adaptation of new varieties (reflected in reduced requirement for vernalization and photoperiod sensitivity) was able to compensate for the negative impact of climatic. The combined effect led to increased wheat yield at Zhengzhou and Luancheng and stabilized yield at Nanyang. In the North China Plain (Zone I), Wang et al. (2008) found a clear trend of warming from 1981 to 2004 in Xifeng (34°44′N, 107°38′E, 1420 m), leading to the earliness of pseudo-stem elongation, booting, anthesis, and maturity by 13.2, 9.8, 11.0, and 10.8 days, respectively. The growth period from seedling emergence to stem elongation shortened 16.1 days, but the growth period from anthesis to milk prolonged 8.2 days. Li et al. (2010) reported that each 1 °C rise in daily mean temperature would reduce the averaged wheat yield in China by 4.6–5.7%, largely caused by the reduction of growth duration. However, Chavas et al. (2009) predicated that aggregate potential productivity of autumn-sown wheat increased by 24.9% under the enhanced CO_2 fertilization effect, based on the Environmental Policy Integrated Climate (EPIC) agro-ecosystem simulation model. Unfortunately, only very few sites located in minor wheat areas were included in the modeling, thus much more work is still needed to understand the impact of climate on Chinese wheat production.

In summary, for winter and facultative wheat in Zones I and II, temperature increases in autumn and improved varieties would allow late wheat planting; a temperature increase in the winter and in the spring benefits the early development for vegetative phase, thus early heading is observed; and the nonsignificant increase or even slight cooling during grain filling period basically maintains the yield, and maturity was slightly advanced, thus allowing the early planting of maize under the wheat/maize rotation system. This has been confirmed by the control trials under warmed at nighttime and unwarmed plots in the Yellow and Huai Valleys conducted by the Nanjing Agricultural University as presented in Table 4 (L. Zhang 2011, unpublished data). It indicated that warmer temperature would benefit wheat production, largely because of the early anthesis, slight advance of maturity, increased grain number per spike, and thousand kernel weight.

Comparison of wheat phenology in representative locations in China between 1980 and 2011 is shown in Table 5. In general, four different patterns have been observed in various regions. (1) Planting date for winter and facultative wheats in Zone I and northern parts of Zone II, including provinces of Shandong and Hebei, was delayed around 7–10 days owing to the temperature increase and extension of new variety conferring tolerance to late sowing, and heading date was advanced around 7 days; however, maturity remains basically unchanged or slightly advanced, thus increased yield was obtained through the extended grain filling duration, which is around 7 days. At the same time, irrigation has been reduced from 4–5 to 2–3 times because of the decline of irrigation water. Direct sowing of maize after harvesting of wheat and the delayed planting of wheat have made the popularity of the wheat/maize rotation system, which has basically replaced the three crops per 2 years system (wheat–maize interplanting or relaying and then cotton) or wheat–maize relay system (maize is sowed around 2–3 weeks before harvest of wheat). (2) Sowing date in Henan province located in the south part of Zone II was also delayed 7–10 days, but heading and maturity remained basically unchanged; therefore, no significant change in the wheat/maize rotation system was observed. (3) Cropping season and rotation system in Zones III and IV remains basically unchanged, although zero tillage is significantly increased to allow the early planting of wheat in the Middle and Low Yangtze Valleys (Zone III) and southwestern China (Zone IV). But significant variation in heading ranging from 6 March to 25 March and

Table 5 Comparison of dates for planting, heading, and maturity in major Chinese wheat locations from 1980 to 2011

Location	*Latitude/altitude*	*Year*	*Cultivar*	*Sowing date (day/month)*	*Heading date (day/month)*	*Maturity date (day/month)*
Beijing	39°48′/31 m	1980	Nongda 139	25/Sept	14/May	18/June
		2009	Jingdong 8	3/Oct	5/May	15/June
Shijiazhuang	38°04′/82 m	1980	Shijiazhuang 54	5/Oct	1/May	8/June
Hebei		2009	Shi 4185	10/Oct	28/April	10/June
Jinan	36°41′/52 m	1980	Taishan 4	3/Oct	1/May	10/June
Shandong		2009	Jimai 22	8/Oct	23/April	1/June
Zhengzhou	34°43′/110 m	1980	Funo	8/Oct	17/April	28/May
Henan		2009	Zhengmai 9023	15/Oct	15/April	28/May
Wugong	34°18′/505 m	1980	Fengchan 3	4/Oct	23/April	10/June
Shaanxi		2009	Xiaoyan 22	10/Oct	20/April	5/June
Nanjing	32°0′/9 m	1980	Ningmai 3	2/Nov	18/April	4/June
Jiangsu		2009	Yangmai 158	5/Nov	18/April	3/June
Chengdu	30°40′/506 m	1980	Fan 6	5/Nov	19/March	15/May
Sichuan		2009	Chuanmai 107	5/Nov	20/March	11/May
Keshan	48°03′/237 m	1980	Kehan 6	5/April	20/June	28/July
Heilongjiang		2009	Kehan 16	3/April	18/June	28/July
Lanzhou	36°06′/1517 m	1980	Ganmai 8	15/March	1/June	15/July
Gansu		2009	Longchun 23	8/March	25/May	5/July
Yongning	38°14′/1118 m	1980	Doudi 1	7/March	5/June	15/July
Ningxia		2009	Ningchun 4	27/Feb	28/May	10/July

Data sources: Collected from senior wheat scientists at each location by Zhonghu He, 1980, 2009 are assumed to be representative of 30 years ago and present.

maturity ranging from 2 May to 15 May was observed in the same location owing to the temperature fluctuation. (4) Planting dates in most spring wheat areas (Zones VI, VII, and VIII) were also advanced around 7 days largely because of the temperature increase in late February or early March, and maturity was also slightly advanced, thus wheat–maize relay has become the dominant system at present.

2.06.3.3 Planting Winter Wheat in the Spring Wheat Region

Winter wheat is more attractive to farmers in China even in the traditional spring wheat area, largely because of its early maturity (thus allows the planting of vegetables and other crops), high yield potential (at least 10–20% higher than spring wheat), and better quality owing to the avoidance of preharvest sprouting. Therefore, the Chinese Ministry of Agriculture initiated a coordinated winter wheat program targeting the traditional spring wheat area, including the provinces of Liaoning, Heilongjiang, Inner Mongolia, Gansu, and Ningxia in the early 1990s, mainly through screening winter wheat varieties from Russia and Canada and modification of cropping management. However, no significant progress has been achieved in most institutes because of the shortage of varieties conferring strong cold resistance and poor snow coverage. After 20 years of continuous efforts, winter wheat has been successfully replaced by spring wheat in Ningxia and part of Gansu and Qinghai provinces. The success of winter wheat is largely due to the benefits of temperature increases and the development of improved winter wheat varieties through crossing local varieties with elite introductions from other countries. Scientists and extension staff are also testing winter wheat in Inner Mongolia and Liaoning at present. Therefore, it is very likely that winter wheat is gradually replacing spring wheat in China.

Spring wheat is a traditional crop in the irrigated area of Ningxia (Zone VIII) where irrigation is provided from the Yellow River, with latitude ranging from 35° to 39° N, and altitude 1100–3556 masl. The basic cropping system includes spring wheat-rice-spring wheat in 2 years and spring wheat–maize relaying in 1 year. Spring wheat is planting from late February to the first week of March, and harvested around 10 July. Winter wheat is planted from 20 September to 10 October, and harvested from 25 June to 30 June, with yield advantage of 2.0–2.5 t ha^{-1} in comparison with spring wheat. With the replacement of spring wheat by winter wheat, maize yield also increased around 750 kg ha^{-1} owing to the early harvesting of winter wheat. More importantly, a new cropping system, that is, winter wheat–forage maize rotation, is well developed and extended. Much more income is generated from the cattle industry by the planting of forage maize. With the release of winter wheat varieties Ningdong 10 and Ningdong 11, the winter wheat area reached 34 500 ha in 2010 and 400 000 ha in 2011, sharing 40 and 50% of the local wheat area, respectively. Zhongmai 175, a winter wheat variety released in North China Plain, also covers around 13 000 ha in the spring wheat area of Gansu and Qinghai provinces. A breeding and germplasm testing program will be needed to support the winter wheat development in Ningxia, Gansu, Qinghai, and Inner Mongolia, although elite germplasm from the Chinese Academy of Agricultural Science station in Beijing perform quite well at present. Efforts should be encouraged to also test winter wheat in Heilongjiang province (Zone VI).

2.06.3.4 Future Perspective

As indicated before, positive benefits of climate were generally observed for Chinese wheat production in the last 30 years, largely due to the delayed sowing of winter and facultative wheat and early sowing of spring wheat. However, negative impact of climate was also significant, including the frequent occurrence of drought, the unpredictable extreme temperature in the winter and the spring, and the increased loss from diseases. For example, more than 100 days of continuous droughts were recorded in 2008–09 and 2010–11 wheat seasons. The arrival of cold temperature in early November in 2009 and slow increase of temperature in the spring of 2010 delayed the wheat season 7–10 days in 2009–10 compared with the average over the last 10 years; thus significant yield loss was observed and also delayed the planting and harvest of maize.

Yellow rust were the major wheat disease, but it is much less significant in Zones I and II at present. In addition to powdery mildew, Fusarium head blight (*Gibberella zeae*), sharp eye spot (*Rhizoctonia cerealis*), and take-all (*Gaeumannomyces graminis var. tritici*) have been well established in Zone II. For Fusarium head blight, acceptable level of resistance is achieved in the autumn-sown spring wheat region (Zones III and IV), but much more efforts are needed in the winter and facultative wheat region (Zone II). It is very likely that damage of Fusarium head blight is becoming more serious than before, largely because of climate and the dominant wheat/maize rotation system. Very little progress has been made in improving resistance to sharp eye spot because of the lack of an effective method for screening resistance and the shortage of resistance in bread wheat.

Because of the temperature fluctuations, a variety with broad adaptation is needed. A favorable genotype under current climate is characterized by slow development before heading (insensitive to photoperiod and temperature) and fast grain filling rate with resistance to high temperature during the grain filling period. High yield potential must be combined with resistance to lodging and tolerance to drought. Therefore, multilocation testing is encouraged in breeding programs.

Much more effort is need to improve crop management, including the management of maize residue in the Yellow and Huai Valleys, so planting quality can be improved. This will significantly reduce seedling rate and winter-kill. Improvement of water and fertilizer use efficiency is also crucially important; this will reduce production inputs and protect the environment.

2.06.4 Climate and Wheat Production in India

2.06.4.1 Wheat Production in India

India is the second largest wheat producer and consumer in the world, after China. Wheat production has increased substantially in the past, from 12.3 million tonnes in 1965 to a record 84.5 million tonnes in 2011 with an area of 29.0 million ha. However, over the last 10 years there have been no significant increases in production, as indicated in Table 6. Therefore, further increase of wheat productivity is a significant challenge.

Wheat area in India is divided into six agro-climatic zones as indicated in Figure 2, but the Indo-Gangetic Plains comprising the Northwestern Plains Zone and Northeastern Plains Zone with high yielding, well irrigated and fertilized conditions share more than 70% of wheat area and produce around 85% of national production. The Central Zone characterized with higher temperatures and less water availability shares around 10% of production. Wheat in northern India is planted in October/November, after rice harvest. Wheat approaches the anthesis and grain filling period in February and March; mean temperature and the frequency of heat days (temperature >30 °C) start to increase substantially in March and April. Therefore, it is crucial that wheat is timely planted, around mid-October, and the anthesis and grain filling period are completed before rapid temperature increase in March and April.

Table 6 Wheat area, average yield, and production in India, 2000–09

Year	*Area (M ha)*	*Average yield (kg ha^{-1})*	*Production (M tonnes)*
2000	27.5	2778	76.4
2001	25.7	2712	69.7
2002	26.4	2758	72.8
2003	25.2	2611	65.8
2004	26.6	2714	72.2
2005	26.4	2591	68.4
2006	26.5	2619	69.4
2007	27.8	2727	75.8
2008	28.0	2807	78.6
2009	27.8	2899	80.6
2010	27.9	2800	80.7
2011	29.0	2900	84.5

2.06.4.2 Impacts of Increased Temperature on Wheat Production

Heat and drought are the two major abiotic stresses, and about 13.5 million ha sharing 50% of the wheat area is considered to be prone to heat stress. However, there is much more information available on the effect of increased temperature and heat shock days (temperature over 30 °C) to production than water availability.

Average annual temperatures in India have increased by 0.5 °C over the past 100 years. Based on the calculations by Aggarwal et al. (2009), each 1 °C rise in regional mean temperature would result in an annual wheat yield loss of 6.6 million tonnes in India. Nelson et al. (2009) hypothesized that rainfed wheat yields in South Asia will decline by around 44% by 2050 owing to alterations in regional climate. Ortiz et al. (2008) reported that by 2050, as a result of possible climate effects in the Indo-Gangetic Plains, currently part of the favorable, high yielding potential, irrigated, low rainfall wheat production megaenvironment (ME1), as much as 51% of its area, might be reclassified as a heat-stressed, irrigated, short season production megaenvironment (ME5).

High temperatures potentially damage wheat throughout the growing season, but the overall impact on yield varies according to their incidence and stages of crop development (Singh 2009). High temperatures in the early season from November to December were reported to have accelerated crop phonological development and as a result reduced yield potential. High temperatures (over 30 °C) can be more damaging during the anthesis and grain filling periods, resulting in significantly reduced yield (Rane and Nagarajan 2004). In many of the dry environments suffering from severe heat stress during grain filling, it has been shown that the enzyme

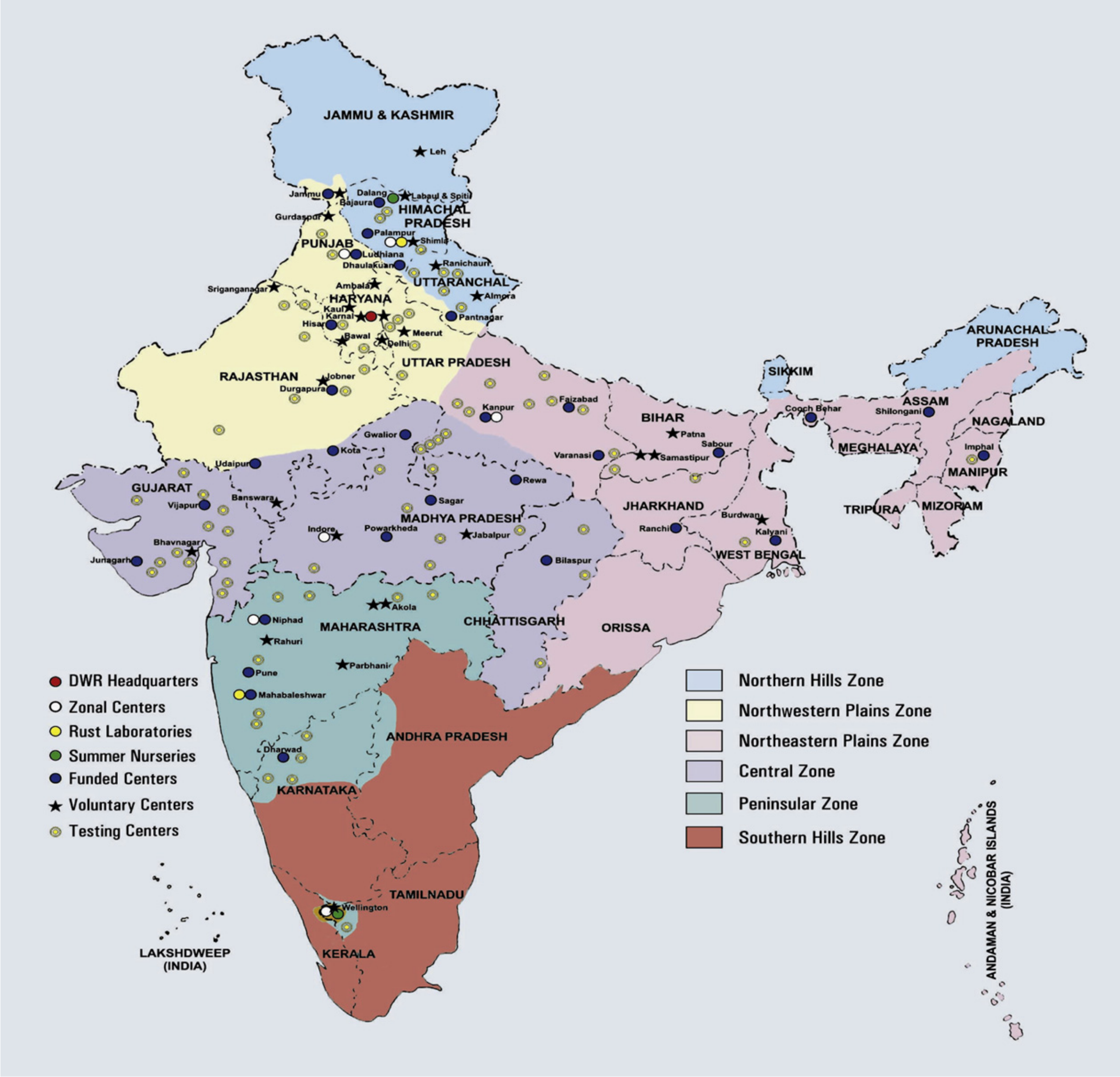
JAMMU & KASHMIR
Leh
Jammu
Dalang
Labaul & Spiti
Bajaura
HIMACHAL PRADESH
Gurdaspur
Palampur
Shimla
PUNJAB
Ludhiana
Dhaulakuan
Ranichauri
UTTARANCHAL
Sriganganagar
Ambala
Almora
HARYANA
Kaul
Karnal
Pantnagar
Hisar
Meerut
Bawal
Delhi
UTTAR PRADESH
RAJASTHAN
Jobner
Durgapura
ARUNACHAL PRADESH
SIKKIM
Faizabad
Kanpur
Cooch Behar
ASSAM
Shilongani
BIHAR
NAGALAND
Gwalior
Patna
Kota
Sabour
Varanasi
Samastipur
MEGHALAYA
Imphal
Udaipur
MANIPUR
Rewa
GUJARAT
Banswara
Vijapur
Sagar
JHARKHAND
TRIPURA
MIZORAM
MADHYA PRADESH
Burdwan
Ranchi
Kalyani
Indore
Powarkheda
Jabalpur
Bhavnagar
WEST BENGAL
Junagarh
Bilaspur
Akola
Niphad
MAHARASHTRA
CHHATTISGARH
ORISSA
Rahuri
Parbhani
Pune
Mahabaleshwar
ANDHRA PRADESH
Dharwad
KARNATAKA
TAMILNADU
Wellington
LAKSHDWEEP (INDIA)
KERALA
ANDAMAN & NICOBAR ISLANDS (INDIA)
● DWR Headquarters
○ Zonal Centers
● Rust Laboratories
● Summer Nurseries
● Funded Centers
★ Voluntary Centers
◎ Testing Centers
Northern Hills Zone
Northwestern Plains Zone
Northeastern Plains Zone
Central Zone
Peninsular Zone
Southern Hills Zone

Figure 2 Wheat zones in India. Kohli M. M., Y. R. Mehta, E. Guzman, L. deViedma, and L. E. Cubilla, 2010: Pyricularia blast – a threat to wheat cultivation. *8th International Wheat Conference: abstracts of oral and poster presentations*, P273, June 1–4, St. Petersburg, Russia.; Lobell, D. B, and M. B. Burke, 2008: Why are agricultural impacts of climate change so uncertain? The importance of temperature relative to precipitation. *Environ. Res. Lett.*, **3** (3), 034007; Sayre, K. D., and B. Govaerts, 2009: Conservation agriculture for sustainable wheat production. *Wheat Facts and Future 2009*, J. Dixon, H. J. Braun, P. Kosina, and J. Crouch, Eds., CIMMYT, 62–69; Whitford, R., M. Gilbert, and P. Langridge, 2010: Biotechnology in agriculture. *Climate Change and Crop Production*, M. P. Reynolds, Ed., *CABI Climate Change Series*. Vol. 1, CPI Antony Rowe, Chippenham, UK, 219–244.

soluble starch synthase in wheat appears to be rate-limiting at temperatures in excess of 20 °C (Keeling et al. 1994). The grain filling of wheat is seriously impaired by heat stress, owing to reductions in current leaf and ear photosynthesis at high temperatures.

Increasing temperatures also would have indirect effects on the incidence of crop diseases and pests, and to grain quality and nutritional value. Both pest and disease populations are significantly affected by temperature, humidity, and elevated carbon dioxide levels (Aggarwal 2008). Singh (2009) reported on the influence of temperature on the incidence of the three rust diseases of wheat – yellow, leaf, and stem rust. In addition, leaf spots and blights (*Helminthosporium*) tend to be more prevalent under higher growing season temperatures. Singh (2009) also postulated that Fusarium head blight incidence could increase in the future. It is not possible to be more definite on these indirect effects of changed climate, but these are important areas for further study.

Water is the other factor influencing wheat production in India. Preseason (October–November) rainfall has generally declined in northern India in recent years, with a more significant decline in North West Wheat Zone. Ground water tables are declining at the rate of 33 cm year^{-1}; losses have mainly occurred in northwest India, whereas there have been increases in central India. Gross per capita water availability is predicted to decline from about 1820 m^3 in 2001 to as low as about 1140 m^3 $year^{-1}$ in 2050 (IPCC 2007). Therefore, an increase of annual temperature and number of heat events, and declined water availability are clearly a risk to future wheat production in India.

2.06.4.3 Future Perspective

Recognizing the potentially and significantly negative impact of increasing temperatures and the decline of water available for agricultural production, the Indian Government requested the Food and Agriculture Organization of the United Nations (FAO) to review the impacts of climate on wheat production in India in September 2009. The review team recommended short-term (1–5 years) and short- to medium-term (5–10 years) implementation of adaptation measures that will bolster future food security and at the same time allow Indian wheat growers to remain productive, profitable, and sustainable. They included measures implemented on-farm immediately, research and development activities for immediate investment, other strategic research and development needs, and economic and policy measures for immediate consideration (FAO 2009). The following part is largely summarized from the FAO Report in 2009.

Short-term adaptations include increasing communication and preparing farmers to cope with climate such as promotion of adaptive research and large scale demonstrations in farmers' fields and strengthening capacity of farmers. Extension of heat tolerant varieties, promotion of conservation agriculture technology, and crop diversification were the major recommended technologies. Studies in both India and Mexico have shown that zero-tilled wheat, with crop residues retained, had canopy temperatures 1–2 °C cooler than conventional planting technology, and resultant higher grain yields (Sayre and Govaerts 2009). It will also allow timely planting to avoid heat stress later in the season, reversing soil degradation, and water and diesel fuel savings. Therefore, accelerating the adoption of conservation agriculture (CA)-based integrated cropping management (ICM) packages for wheat-based systems was strongly recommended. Diversification of cropping systems includes enhancement of relay/intercropping systems, promotion of more water efficient crops such as maize and barley, inclusion of legumes in rotations, shifting from long duration rice varieties to medium duration varieties, and allowing more timely planting of wheat.

Short- to medium-term adaptations include development of new wheat varieties with super heat resistance, higher water use efficiency, enhanced disease and pest resistance, and ability to respond to elevated levels of atmospheric CO_2. In order to accelerate the selection and breeding of these new varieties, new molecular approaches will be necessary to achieve the efficiencies and effectiveness desired. Field evaluation for a trait such as heat tolerance and improving water use efficiency has proved difficult, and marker-assisted selection is likely to achieve greater success (Hays et al. 2007; Richards et al. 2010; Mason et al. 2011). Improvement of conservation agriculture-based technologies is also needed, including better varieties and more adaptive and diverse systems. More research is required on understanding genotype and conservation agriculture technology interactions, diversification of wheat-based systems to include a broader range of crops including durum wheat, maize, oilseeds and pulses, and increase water use efficiency.

2.06.5 Conclusion

Much more research is definitely needed to have a clear understanding on the impact of climate on wheat production. It offers great opportunity and challenges for policy makers, farmers, and agricultural scientists. Basically there are two technical approaches to copy with climate, that is, crop management and improved varieties, and various aspects have been reviewed in *Climate Change and Crop Production* (Reynolds 2010). The strategies for developing new cropping systems include use of crop models in decision-making, applying remote sensing and precision agriculture technologies, monitoring crop condition, optimized water use efficiency, and optimize land use (CSSA 2011). Crop diversification including testing and adaptation of new crops and cropping system as recommended for India can maintain relatively good productivity under climate changing conditions; it may also generate high income for small farmers. Conservation agriculture based on minimal soil disturbance, permanent ground cover, and crop rotation has proved to be a powerful technology particularly under rainfed conditions, to reduce soil erosion, increase water use efficiency, early planting of wheat under the rice/wheat rotation system, and increase productivity (Hobbs and Govaerts 2010). Development and adaptation of new varieties that combine high yield potential with enhanced tolerance to high temperature and water use efficiency will be an economical friendly approach for increasing wheat production. Molecular markers assisted selection (MARS) and genetic transformation (Whitford et al. 2010) can play an important role for improving drought and heat tolerance. However, conventional breeding is still the most powerful approach to develop new varieties, and multilocation testing remains the most efficient system to identify varieties with broad adaptation to various geographical locations, and wide ranges of environment and management conditions. The strategies for improving existing varieties and developing new crops include (1) develop new crops; (2) integrate beneficial traits into existing crops through use of germplasm collections, rate datasets, and breeding; (3) use new technologies, image-based measurements, high throughput DNA sequencing, databases, and statistical models; (4) identify crop germplasm that tolerates drought, heat, and water logging; (5) expand field level evaluations of crop germplasm; and (6) employ new tools, techniques, and datasets to accelerate the delivery and release of proven varieties (CSSA 2011). In the long term, research investment and efforts are needed to further understand the physiological, genetic, and molecular basis of adaptation to drought, heat, and biotic stresses from the climate; translate new knowledge into new agricultural systems that integrate genetics and management technologies; and transfer knowledge effectively and make technologies and innovations widely available to increase food production and stability (CSSA 2011).

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2.07 International Fisheries and Climate Change

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Marine capture fisheries are a critical source of high quality protein in many areas around the world, providing a billion people with more than 20% of their animal protein (FAO 2009). Many of the people most dependent on fishery production are in impoverished communities located in small island states, South Asia, Southeast Asia, and Africa (FAO 2007). Globally, overall fishery production from both capture fisheries and aquaculture (144 million tons in 2006) provides nearly 17 kg of fish per capita. These figures give a simple picture of the importance of fisheries for global food security. Fisheries resources, whether in coastal waters or on the high seas, are highly vulnerable to long-term environmental change, including climate change, because production is dependent on the underlying natural system. Climate impacts such as ocean temperature increases can profoundly affect production of natural and cultured stocks including changing growth, reproduction, survival, and other critical life history features of exploited stocks and the ecosystems that they depend upon (FAO 2008; Garcia and Rosenberg 2010).

In the developed world, fisheries are often out of sight and mind, in some sense obscure to a large part of the population. Yet fisheries are the last great hunting and gathering means of food provisioning around the globe and are subject to very different pressures as environmental change occurs, compared to land-based agriculture. Fish and fisheries can change rapidly, and sometimes dramatically, from area to area, in species composition, in the fishermen that have access, and the level of production available. Like all food production, fisheries are completely dependent upon natural systems to support productivity. But unlike land-based agriculture, humans can only directly control fishing activity, not the underlying system that produces the fish. In other words, capture fisheries are still wholly dependent on the natural productivity of the ocean. While aquaculture is increasing rapidly and now accounts for half of the fish production for human consumption globally, it too can only be sustained by natural systems. Aquaculture requires habitat (e.g., circulating water of high quality and the right characteristics), nutrients, feed, and space within natural systems. While culturing alters systems to enhance productivity, very specific conditions are still required for success whether on land or in the sea.

Climate will be a major driver of vulnerability in fisheries in the coming decades, but not the only human-induced driver of change and potential depletion. Both capture fisheries and aquaculture have a history of overexploiting the natural systems upon which they depend. For capture fisheries, overexploitation results in reduced abundance of many species, habitat loss due to the impact of fishing (and other activities), reduced size and value of the fish in the catch, and in some cases fundamental changes in the marine ecosystems supporting fish production (NRC 2006). For aquaculture systems, overexploitation takes a different form, causing loss of habitat due to siting of farms, effluent, disease and other direct environmental impacts, competition for coastal space, and the use of wild caught fish for feed. In both cases, production, if not well managed, increases the vulnerability and reduces the resilience of marine ecosystems to changing conditions (Carpenter et al. 2001; NRC 2006). For example, a well-managed fishery maintains the exploitation rate (proportion of the stock removed by harvesting each year) at levels below that which can, on average, be replaced by natural production each year. In the course of this, the size and age composition of the population have a fairly broad distribution such that the fishery is not strictly dependent upon annual reproduction in each year. But in an overexploited fishery, the harvest becomes increasingly dependent on annual reproduction, and the result is that one year of poorer reproduction can result in major declines in the stock of fish in the ocean. There is no buffering effect of having multiple years of reproduction present in the population, and vulnerability to poor environmental conditions is increased. Similarly, if aquaculture is highly concentrated in one area, the water quality is degraded and disease prevalence is not controlled, then production is vulnerable to poor conditions in any one year, and to new outbreak of disease or other effects.

In contrast, well-managed systems have higher abundance and diversity, and are able to maintain resilience to these kinds of environmental effects with a greater capacity to bounce back from perturbation. In the context of climate impacts, fisheries that are not overexploited can be expected to 'weather' climate variability and change in average conditions better. This is essentially analogous to the portfolio effect often referred to in investment strategies. Having a single investment type, or in the case of a fishery a single resource (e.g., species, age groups), is highly vulnerable to loss due to changing conditions. However, a diversified portfolio is buffered against losses in any one element of the portfolio. Overharvesting effectively reduces the scope of the portfolio of fishery resources, and so is an inherently risky strategy, particularly in the face of a changing climate. Note that this conclusion does not require in-depth knowledge of exactly how any given fish stock in the portfolio will respond to climate. Diversification of investment in the face of uncertainty is a well-known approach to reducing risk, and is directly applicable to sustaining fisheries.

Climatic changes have and will affect ocean and coastal areas in many ways. The most direct are increasing water temperature, rising sea level, and increased acidity of the water (IPCC 2007; Cooley and Doney 2009). In addition, changes in precipitation and runoff of freshwater, land-based sources of sediment and nutrients, changes in severe weather frequency, and intensity are likely to have major impacts. From a fishery and aquaculture perspective, these changes will result in habitat

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changes for commercially important species of fish and shellfish, and changes in availability of resources to fishing communities (Barange et al. 2010a,b). Habitat changes such as increasing water temperature, changes in coastal nursery areas such as mangroves and salt marshes due to sea level rise, or changes in nutrient dynamics that effect ocean primary productivity will result in changes in fish production – both increases and decreases. In a general sense one might expect fish populations to move poleward and deeper as temperatures increase, to stay within their thermal tolerance ranges. As such, some areas will become more productive for certain species and some less so for those same species (Brander 2007; Cheung 2009). But, it is not as if there are areas of the ocean that are currently not utilized. Distributional changes will undoubtedly not happen in concert as different species will adapt to changing conditions at differing rates, because life history strategies (generation times, growth rates, etc.) differ widely among fish species and populations (Barange and Perry 2009). Predator and prey may adapt at different rates, and new prey or predators may become important in a given ecosystem (Stenseth et al. 2002). Spawning sites take time to be populated and productive for many species, and nursery area proximity to spawning grounds may be greatly different. All of these changes result in great uncertainty in the adaptive capacity of any given stock of fish to changing climatic conditions. Of course, this process has been going on for millions of years as natural populations have adapted to changing environments. Two things are different in the current course of environmental change; observed climatic changes are much more rapid than in the past millennium, and human exploitation and other environmental impacts have altered adaptive capacity of natural populations in multiple ways (Miller et al. 2010).

From simple ecological theory, some species are likely to be favored (with regard to productivity at the population level) by rapid environmental change and others are vulnerable. This of course adds to the uncertainty. Already, some increases in productivity are apparent in sub-Arctic and Arctic areas from temperature increases (Stenevik and Sundby 2007; Brander 2007). But how this is changing food webs in these areas is an open question (Pauly et al. 2000). Other analyses suggest that there will be large-scale depletion of fishery resources in the tropics, but this may be an artifact of our lack of knowledge of the adaptive capacity of tropical species (Cheung 2009). If the temperature tolerances of the current set of commercially important species remain unchanged, then poleward and deeper shifts in distribution will deplete tropical areas that support some important fisheries. In general, it is hard to estimate which species will move in to replace those whose distributions shift. But, nature usually does not leave a vacuum, so again the uncertainly is high. Tropical area fisheries are particularly critical to food security for some of the poorest peoples, so even the potential for large reductions in fishery productivity must be addressed.

Productivity of fish stocks, and potentially aquaculture operations, may additionally change because of physiological responses to warming or other habitat changes. In some cases, faster initial growth, but smaller adult size for some species may result, impacting fishing or culturing operations (e.g., processing, marketability), as well as food web considerations. Aquaculture is an interesting case. Domestication selection for culture stock obviously speeds up the process of adapting to culture conditions (habitat) and market considerations; however, many operations are dependent upon specific strains and adapting to future unknown conditions, to say the least, challenging both technically and from a business perspective. Case in point is the apparent impacts of ocean acidification that are already occurring for some shellfish aquaculture operations in the US Pacific Northwest (J. Buizer, personal communication). Settlement of larvae has been impaired in some cases because of lower pH and selection for more tolerant strains may already be underway. Even though this selection may occur faster than in nature, will it be fast enough for commercial purposes?

In fact, many of the concerns over the impacts of climate on fishery and aquaculture production come down to uncertainty about rates of change. How fast will distributions shift? How quickly will species life histories adjust? How quickly will food webs alter? What will be the time course of change in productivity (both increases and decreases)? These rates are difficult to predict which means that monitoring of fisheries and aquaculture will be increasingly important to avoid loss of resources. The consequences of allowing rapid expansion of fisheries as some stocks extend or shift their range, for example, into Arctic waters, are overexploitation and the loss of real opportunity for food production. From the history of fisheries, it is clear that fishing pressure on a stock can and will expand very rapidly once an opportunity is identified, unless strong regulatory controls are in place (Rosenberg 2003). The result is a rapid increase in catches to unsustainable levels and a decline in the resource, sometimes a real collapse (e.g., Northern cod in Canada in the 1990s, fisheries on seamounts in the 1990s and 2000s), followed by poor or no catches for many years due to the loss of productivity (Garcia 2009).

Similarly, if productivity is declining due to climate effects (at an unknown rate without monitoring), then overexploitation or the loss of adjustment time for the industry will likely result with dislocation of fishermen along with loss of food production. So the need to monitor distributional changes, productivity rates, and habitat changes is crucial for both fisheries and aquaculture, along with a need for strong management controls to ensure sustainability of both the resource and the industries that depend upon them.

Climatic impacts cause increasing stress not only on natural resources, but also on the industries and people that depend upon them, as well as the management systems intended to conserve the resources (Miller et al. 2010). Fishing and aquaculture businesses will struggle to adjust not only to changing resources, but to increasing stress in ocean areas from population shifts, changes in coastal areas that affect coastal access, as well as coastal habitat for fishery or aquaculture resources, the impacts of increasing severe weather events, and the effects of climate on other food resources (Perry et al. 2010). If fishery stocks shift in distribution, then access and costs to reach fishing grounds will change. Sea level rise will change port and landing facility conditions, including vulnerability to natural hazards. And, the loss of availability of other food resources including agricultural production and wild food harvest on land can increase pressure on fisheries, particularly for subsistence or small-scale fishermen.

Large vessels with greater range will certainly have the ability to adjust to changing fish stock distribution patterns.

However, the capability to operate farther afield is not a full measure of adaptive capacity for fishing businesses, since larger vessels require greater catches, and therefore stock productivity (or a larger share of the catch that is available), than smaller vessels. It is not easy to predict how the availability of stocks will affect allocations between different sizes of vessels, but it is clear that there are likely to be changes and that such change often results in conflicts between groups of fishermen. These conflicts occur between vessel size categories, gear types, vessels from different communities, or vessels from different countries, and often take a long time to settle into a stable agreement. Adding environmental changes in productivity and distribution of resources to this uneasy setting can clearly destabilize fishing agreements, formal or informal.

Similar to allocation agreements between groups of fishermen, many management measures designed to protect against overharvesting, habitat damage, or conflicts between fishing groups may be destabilized by changing environmental conditions (Miller et al. 2010). This is particularly so because the effects of climate change, are likely to be trends with a consistent direction (long-term increases or decreases in stock in a particular fishing area), though increases in variability of productivity may also be expected as natural resources adapt to changing conditions. In general, fishery management systems are designed around the assumption of stationarity in the underlying dynamics of the ecosystem, that is, these ecosystem properties have a constant mean and variance. Changing conditions that alter the average or variability of say productivity or species composition may mean the current management system will no longer be appropriate. For example, total allowable catches may need to be continually adjusted just to maintain exploitation rates constant through time if particular stocks decrease (increase) productivity. Allocation of the catch of various species between user groups may be fundamentally compromised by long-term changes in abundance and species composition. Reopening allocations or ongoing reductions in total allowable catches have enormous potential for disruption and conflict, since many contentious fishery management issues are about allocation between user groups in the first place. Similarly, the efficacy of closed areas or marine reserves may be affected by distributional shifts in species at different life stages. Again, the establishment of reserves in any fishery is often contentious because of the impacts on the allocation of fishing opportunities to different fishing groups. If changes in habitat, including temperature and other effects of climate change, mean that reserve areas must be renegotiated, then this is a major task for fisheries' managers and fishermen alike. The question of rates of change also arises: How long will a reserve be adequately sited if the location of spawning, feeding, or nursery grounds for various species are moving?

In the last two decades, there has been a shift toward the so-called 'rights based fishing' around the globe. That is, allocating fishing privileges or 'rights' with attendant responsibilities to adhere to conservation rules, to individual vessels, or groups of vessels, or communities. In this context, these rights include the full spectrum of systems from Individual Transferable Quota systems to Territorial Use Rights for an indigenous community (Beddington et al. 2007). But the systems have been constructed, as noted above, under the assumption that the natural system is stationary (constant mean and variance), which under climate change will likely no longer pertain. How will hard-won allocations to communities or businesses be altered by the effects of climate change on fishery resources? Distributional changes, productivity shifts, and ecosystem changes may make previously stable allocations highly unstable. Even if change is relatively slow, management systems will need time and information to adjust, given the difficulties of negotiating new arrangements for fisheries.

All of the above considerations apply for both national fisheries and those in international waters. Generally, high seas fisheries are governed by treaty organizations, as well as the provisions of the UN Law of the Sea. Regional fishery management organizations, composed of treaty member states that fish or have interests within a region, exist, for example, on both sides of the North Atlantic, in the Baltic, the Mediterranean, the Antarctic, the southeast Pacific, and for tuna fisheries in the central and western Pacific, the Indian Ocean, the Atlantic, and the eastern tropical Pacific. These organizations have been set up to manage fisheries with a focus on resource sustainability and allocation among member states. While they, like all fishery management, have a mixed record of success on sustainability of resources (Beddington et al. 2007; Garcia and Rosenberg 2010; Mora et al. 2009; Worm et al. 2009), they are the principal mechanism for limiting fisheries on the high seas. Illegal or unregulated fishing outside of national or international control is still a major issue (FAO 2001; Agnew et al. 2009), but will best be addressed by individual states and international organizations under treaty and Law of the Sea authorities (e.g., agreements on flag and port state responsibilities). These organizations will also need to deal with changing distribution and productivity of stocks under their jurisdiction (agreement between member states) with the added complication of having to negotiate between sovereign states. Virtually all such regional fishery agreements maintain the sovereign right of objection for members; they may act unilaterally if they cannot agree to management measures set by the organization. In other words, their participation and acceptance of management measures is voluntary and cannot be compelled by other states. This in effect slows the time it takes to make adjustments to changing conditions for fishery resources. The rate of change in fishing strategy, management effectiveness, and allocations between user groups is necessarily that of the member state that is willing and able to adjust most slowly. Similarly, controlling fishing opportunities in new areas or for newly productive resources to avoid overcapitalization and overharvesting will only occur with concurrence of all states capable of fishing within a region, unless preemptive action is taken to limit fishery expansions. Some international fishery management bodies have agreed to such preemptive action (e.g., in the Antarctic under the Commission for the Conservation of Antarctic Living Marine Resources), but it is not the norm. Climate effects on fisheries will make a precautionary approach to fishery management (FAO 1996) even more critical to avoid depletion of major fisheries.

In summary, the fisheries of the world will be vulnerable to long-term changes in climate biologically and from a policy perspective. While the actual time course of changes in fisheries resources is highly uncertain, it is quite certain that there will be major changes in productivity, distribution, and sustainable yield. This will affect the efficacy of management systems around the globe and the businesses, people, and communities that depend on fisheries for livelihood and food security. While there are clear needs to improve monitoring of fishery resources and fisheries to better understand the changes that are occurring, it is essential that a precautionary approach to management be implemented, as broadly as possible, in order for fisheries to continue to serve as a major source of food, employment and enjoyment globally.

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2.08 Climate Vulnerabilities of the Poultry Industry

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2.08.1 Introduction

The primary impacts of climate on poultry production relate to resource competition (feed and water), disease and pest pressures, and a need to adapt to and manage the impacts of extreme and variable environments. These impacts are not unique to poultry production, but the reliance on current feed inventories, housing and ventilation systems, and adequacy of current biosecurity measures may translate to greater challenges for poultry and swine production systems, than for dairy and beef production systems that make use of open housing facilities and a wide variety of feeds and by-products that can be effectively digested by ruminant species. Challenges present opportunities for livestock production. Higher level of management offers the advantage of better control of input costs and ability to manage the impacts of extreme weather events as well as adapt to new and different market opportunities such as different feed ingredients or practices to reduce on-farm fossil fuel use. In a scenario in which a minimal contribution to climate occurs by livestock production (per unit of product) and is rewarded, the level of management and ability to adapt will determine those operations that will remain successful.

2.08.2 Contribution to Climate

On a global basis, FAO (2006) estimated that poultry production is responsible for 0.36 million tons of N_2O emissions per year as a result of applying poultry manure to croplands. Approximately 25% (or 0.09 million tons year^{-1}) originates from 'industrial agriculture' (see *Climate Vulnerabilities of the Swine Industry*, **Table 1**). Poultry production in North America occurs primarily in confined housing systems on large production units (see *Climate Vulnerabilities of the Swine Industry*, Table 1), contributing an estimated 0.04 million tons of N_2O year^{-1}, similar to that from swine and dairy production in North America. Estimates by the U.S. EPA (2011) indicate that 7.3% of US anthropogenic greenhouse gas (GHG) emissions, expressed as carbon dioxide equivalents (CO_2-eq), originate from agriculture. Enteric fermentation is the second largest source of CH_4 emissions, behind natural gas systems (U.S. EPA 2011). Burns et al. (2008) reported 5.24 Mg GHG emissions (CO_2-eq) monitored from broiler houses located in southeastern United States (per 1000 birds raised for 52 days). Their results indicated that CO_2 contributed to 88.6% of the total GHG emissions. Verge et al. (2009) for the year 2006, reported Canadian GHG emission inventories based on live weight (CO_2-eq) for broilers and culled layers at 1.0 kg hg^{-1}, turkeys at 1.44 kg hg^{-1}, and eggs at 1.73 kg per 12 eggs, respectively. Available literature indicates that poultry CH_4 emissions from enteric fermentation are negligible. Emissions of N_2O are the result of manure management land application of poultry manures.

Poultry manure management contributes a relatively small amount to global methane production from livestock systems (see *Climate Vulnerabilities of the Swine Industry*, **Table 2**; FAO 2006). Management of poultry manures in North America emitted approximately 0.16 million tons of CH_4 in 2004 (see *Climate Vulnerabilities of the Swine Industry*, Table 2). **Table 1** shows the CO_2-eq of US GHG emissions inventory from 2005 through 2009 from poultry manure management, whereas **Table 2** depicts the total GHG emissions from manure management (U.S. EPA 2011).

Wang and Huang (2005) estimated housing CH_4/N_2O emission based on life cycle analysis as from broiler chickens, Taiwan country chickens, and white Roman geese at 15.87/0.03, 84.8/16.4, and 1500/49 (mg per bird for life cycle), respectively. They calculated broiler enteric fermentation CH_4/N_2O emissions as 3.03/0.006, 14.73/2.84, and 9.5/0.31 (Mg year^{-1}), respectively, in Taiwan for the year 2000.

The AEA (2010) report estimated total CH_4 emissions from poultry operations in the United Kingdom as 12.64 Kt for the year 2008 and reported zero enteric CH_4 emissions. Although

Table 1 Methane and nitrous oxide emissions from poultry manure management in the United States (Tg CO_2-eq)

Gas	*2005*	*2006*	*2007*	*2008*	*2009*
Methane	2.7	2.7	2.8	2.7	2.7
Nitrous oxide	1.7	1.7	1.7	1.7	1.6

From: U.S. EPA., 2011: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2009. 2011 EPA 430-R-11-005. (2011). [Available online at http://www.epa.gov/climatechange/emissions/usinventoryreport.html.] Accessed December 1, 2011.

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Table 2 Methane and nitrous oxide emissions from poultry manure management in the United States (Gg)

Gas	*2005*	*2006*	*2007*	*2008*	*2009*
Methane	129	131	134	129	127
Nitrous oxide	5	5	5	5	5

From: U.S. EPA., 2011: Inventory of U.S. Greenhouse Gas Emissions and Sinks: 1990–2009. 2011 EPA 430-R-11-005. (2011). [Available online at http://www.epa.gov/climatechange/emissions/usinventoryreport.html.] Accessed December 1, 2011.

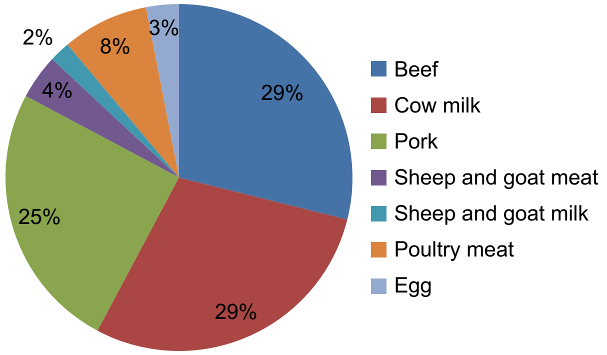

Figure 1 Total GHG fluxes of EU-27 livestock production in 2004, calculated with a cradle-to-gate life cycle analysis with common agricultural policy regional impact (CAPRI) model. Adapted from Leip, A., and Coauthors, 2010: *Evaluation of the LivestocKs Sector Contribution to the EU Greenhouse Gas Emissions – Final Report*, European Commission Joint Research Center. [Available online at http://www.fcrn.org.uk/research-library/meat/livestock/report-evaluation-livestock-sectors-contribution-eu-greenhouse-gas-emissions.] Accessed December 1, 2011.

this report estimated N_2O emissions from agricultural sector as a whole; however, this report did not estimate the N_2O emissions from poultry operations. Lesschen et al. (2011) reported GHG emissions for 27 European Union countries (EU-27) for poultry and egg at 1.6 CO_2-eq kg^{-1} and 1.3 CO_2-eq kg^{-1}, respectively. When summarized by livestock sector for EU-27, the poultry accounted for 6% of the total GHG emissions. Weidema et al. (2008) based on life cycle analysis (LCA) model assessed the impact of GHG emissions (CO_2-eq.) from EU-27. They reported 5–10% of the GHG emissions come from poultry sector and 3.6 kg CO_2-eq kg^{-1} by poultry weight basis. In a review paper, de Vries and de Boer (2010) from 16 European studies based on LCA method reported that production of 1 kg chicken resulted in 3.7–6.9 kg CO_2-eq, and production of 1 kg eggs resulted in 3.9–4.9 CO_2-eq. Figure 1 illustrates the livestock sector contribution of GHG emissions in EU-27 calculated based on the LCA method using the CAPRI model (Leip et al. 2010).

2.08.3 Vulnerabilities

Poultry flocks are particularly vulnerable to climate because birds can only tolerate narrow temperature ranges. Higher temperatures increase risks of heat stress in flocks and can result in reduced egg production and growth rates. IPCC predictions depict increases in mean annual temperature by as much as 2 °C over the next century (Meehl et al. 2007). The challenges posed by increased temperature may be either decreasing productivity or increasing cost. Although confined systems have the advantage of being able to control the indoor environment, it is at an economic and energy cost. To maintain productivity, housing systems need to be managed to maintain optimal temperatures, and increased investment will be required in ventilation and cooling to counteract higher temperatures. Often water is used to provide cooling. But as discussed, water resource concerns may limit the expansion of this practice and may even require that alternatives be found. Increased use of fossil fuels to provide cooling is not desirable when in a situation in which the objective is to reduce the carbon or environmental footprint of the farm. This leaves use of renewable energy or bioenergy sources to provide cooling. To maximize 'free cooling' building designs and design of ventilation systems may require reconsideration. Stocking density may need to be reduced in extreme temperatures, potentially increasing costs. The depressive effect of heat stress may increase the rate at which poultry bird consumes water and consequently reduce the egg shell thickness (Kekeocha 1985). Also, it has been reported that preconditioning broilers to heat stress to encourage better survival during transport could lead to more variable breast meat pH and affect meat quality (Gregory 2010). Furthermore, extreme weather events, such as storms, would increase stress and may adversely affect productivity, and cause higher mortality, especially for outdoor flocks.

In addition to engineering solutions that provide an adaptation mechanism for climate, there is a longer term need to consider animal genetics and opportunities with genetics to develop an animal that is productive while more resilient to temperature extremes, particularly heat stress. Current breeds that are heat tolerant tend to have lower productivity. To meet the food needs of a growing human population that, globally, desires more animal protein, heat tolerant breeds that do not compromise performance need to be developed.

Plausible future climatic conditions suggest that in some parts of the world extended drought periods would further challenge water supplies and competition between water use for households and drinking water versus water use for agriculture production. In other parts of the world, annual precipitation may increase, but this may be accomplished through increased frequency of extreme events. Animal housing infrastructure and maintenance may have to cope with more intense weather events and increased rainfall. This also has implications for sizing manure storage structures. In many areas the amount of rain projected from a 25-year, 24-h storm event could increase, thereby increasing the size of manure storage needed to accommodate that rainfall that directly deposits into the manure storage as well as that collected from the production area if roof runoff is not redirected away from lots. For most poultry operations, birds are raised in confinement, precluding the need to collect roof runoff. In litter and stack systems, typical of most poultry production facilities, litter remains in the house or under the roof until land applied; thus, the manure storage issues associated with increased precipitation resulting from a 25-year, 24-h storm event can be avoided. However, this challenge remains for most swine, dairy, and beef operations.

2.08.4 Resource Competition

Some of the indirect effects of climate are through feed resources, the buffering abilities of ecosystems, increased desertification processes, increased scarcity of water resources, lower production of grain, and so on (Thornton et al. 2007). There are also challenges related to the potential shortage of feed owing to a rapid increase in production competition among food, feed, fuel, and land use systems. With increasing production of biofuel crops on finite land resources, the price of corn is presently priced at an all-time high. In spite of constant improvements in yield, increased arable acres devoted to biofuel crop production coupled with increasing demand on grain as a food crop for a growing population creates competition among bioenergy, food, and feed demands. This leaves livestock production in a vulnerable position if it is to remain profitable. Ruminant species can take advantage of forage crops unsuitable for human consumption; leaving competition for forage crops to be had between bioenergy and feed purposes. Nonruminant species, such as swine and poultry, cannot digest high-fiber forage feeds and therefore rely heavily on grain crops. Climate affects swine and poultry industries indirectly by its impact on the availability and price of crops used for animal feed. More pressure will be put on the swine and poultry industries if the extensive grains industry is affected. If cropping regions are shifted, the swine and poultry industries, which are mostly located in current cropping regions, will have to be relocated accordingly or deal with increased transport cost of feed.

Co-products and by-product feeds offer promise as energy and protein sources for the livestock industries. Some by-products, such as distillers dried grains with solubles that result from grain-derived ethanol production, have been thoroughly investigated a feed for laying hens, broiler chickens, and turkeys. At present, recommended diet inclusion levels are at no more than 20% of the diet, replacing corn and some soybean meal (Applegate et al. 2009; Wang et al. 2008; Ferket and Gernat 2008). Other by-product and co-product feeds need similar assessment before these alternative feeds can effectively be adopted by the industry. However, access to feeds and affordability of feeds will drive the need to conduct the necessary research that provides recommendations for inclusion of nontraditional feedstuffs. Regardless, it is unlikely co-products and by-products can completely replace primary grains in poultry diets, leaving some competition inevitable.

One of the trade-offs of using co-product or by-product feeds is that nutrients are more concentrated than in the original grain. This includes a concentration of nitrogen, phosphorus, and fiber. Often, these feeds are included in diet formulation as a protein source and the overall diet is not different in protein content between the formulation with the grain and the formulation with the by-product or co-product. Phosphorus content, however, can be considerably greater in the diet containing the co-product or by-product feeds resulting in greater phosphorus excretion in manure unless removal of supplemental dietary phosphorus can offset the contribution from the co-products or by-products. Excessive manure phosphorus has surface water quality implications if not managed properly. Dietary fiber increases as a result of dietary inclusion of co-product or by-product feeds. This increases fiber content of manure and manure mass and volume excreted (Applegate et al. 2009), necessitating greater storage area for manure. Because the amount of storage area needed for manure is increased, the overall footprint of the farm may increase (surface area) and the surface area of the manure storage likely increases, providing the potential for more emissions to result because of the increased size of emitting surface.

Water resources, like land, are finite and we already see competition for water. Meat birds (broiler chickens and turkeys) grown in litter-based housing systems use minimal water. Drinking water is the primary use and far surpasses quantities used for other purposes, on farm. Laying hen facilities with egg processing onsite use water for cleaning eggs (3300 m^3 per ton of eggs) (Mekonnen and Hoekstra 2010). In addition, some poultry facilities use water as part of a cooling strategy. With increasing mean temperatures and increasing frequency of extreme events, including heat waves, the need for cooling in confined systems is expected to increase. Animal agriculture may come under scrutiny for its water consumption. Although poultry production uses less water than other livestock systems (i.e., dairy and swine) it is not immune to the effects of water shortfalls or consumer demand to reduce the water footprint of food production.

2.08.5 Diseases and Pests

Increasingly in crop production new pests are being found in areas in which they were previously absent. Examples include the brown marmorated stink bug and spotted wing *Drosophila*. Alpine forests in Canada have fallen prey to pests that previously were excluded because of a shorter growing season. Pest prevalence is changing, and this change has been attributed to increasing mean temperatures, milder winters, and longer growing seasons (Patterson et al. 1999). Increasing temperatures evaporate more water into the air and cause a proportional rise in humidity that provides a medium for fungal and bacterial growth. There are chances of increased persistence of some endo- and ectoparasites and increased mycotoxins in feed associated with increasing temperatures. Disease prevalence and strains of diseases, including viruses and pathogens, may have long-term implications for poultry production. Bronchitis is among the few that are transmitted via moist air breathed by the birds. At risk are animal productivity and the potential for transfer of disease to humans.

Complicating the situation is increased societal pressure to minimize or eliminate preventative or nontherapeutic administration of antibiotics in feed and water. Although routine vaccination is common practice in modern livestock production, vaccination protocols are uncommon in meat bird production because of the short lifespan of the animals (42–49 days for broiler chickens, 16–22 weeks for turkeys), and consumers express concern over resistance to common vaccines. Adaptation to increasing disease challenges might require more advanced biosecurity protocols or a change in housing practices to facilitate better interruption of disease cycles. Practices could include reduced animal density within animal housing, potentially increasing the footprint of a farm and increasing the product cost to the consumer.

2.08.6 Mitigation Opportunities

On-farm energy generation is one opportunity to mitigate the contributions of livestock production to climate. The impacts of on-farm energy generation through the use of anaerobic digesters are discussed in greater detail elsewhere in this book. Although anaerobic digestion is considered an option for liquid manures, for drier manures such as those generated in poultry production the potential is more limited owing to mixing and flow challenges. A more promising alternative is gasification. Not widely adopted in agriculture systems, use of gasification is on the rise, particularly in Europe and installations are underway in the United States. The economics and potential to offset fossil fuel use needs further evaluation at commercial scale.

Poultry are the most efficient converters of feed to food product of all livestock species. Further improvements in feed efficiency through animal genetics can further reduce manure production mass, thereby offsetting the challenge of needing greater manure storage as a result of feeding co-product or by-product feeds. Improvement in feed conversion efficiency has the added benefit of decreasing the pressure to access and afford grain as a staple ingredient in the poultry diet.

Poultry housing systems are presently designed to minimize water contamination by manures throughout the manure storage phase. Capture and treatment of gases exhausted from buildings (NH_3) offers an opportunity to reduce contributions to N_r. Opportunities exist to minimize N_2O losses when manures are stored in the field before land application and following land application of manures. Managing timing of land application, optimizing soil moisture content at time of manure application, and minimizing time that litter sits in a field uncovered are all opportunities to reduce the environmental impact of poultry production.

2.08.7 Conclusion

Global food demands must be balanced with reduced environmental impact of food production. As the growing global populations seeks to incorporate more animal protein in the diet, the production of animal protein must be met while addressing challenges posed by climate. The challenges include direct effects of climate on the animal, as well as indirect effects through feed supply or disease susceptibility that are affected by climate. This will require that the poultry industry think creatively about how to produce meat and eggs in a manner that is profitable and less reliant on traditional feed resources, fresh water supplies, and fossil fuels.

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http://www.ipcc.ch/index.htm Reports from the Intergovernmental Panel on Climate Change.

2.09 Climate Vulnerabilities of the Swine Industry

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2.09.1 Introduction

When considering how swine production is affected by climate, perhaps the best place to start is to consider the present day vulnerabilities of the industry. The swine industry, like most of the meat production industry, is based on intensive production (Aneja et al. 2009) with trends suggesting future increases in intensification. This industry model depends on cheap grain, cheap energy, and manageable disease control. Zhao et al. (2005) opined that plausible changes in temperature, and precipitation frequency and intensity may have direct impacts on nonintensive swine production, but is not likely to directly affect intensive production because the barn environment is controlled. However, an increase in the frequency of both severe storms' (e.g., hurricanes, tornadoes, etc.) intensity and severity is also plausible. Increased storm intensity might be expected to increase the likelihood of upset of large open-air lagoon treatment systems, and increased severity has the potential to inundate the barns (Aneja et al. 2001). This could lead to increased pressure on intensive operations to modify current manure treatment systems. Climate could have negative impacts on feed grain production which would affect its availability and price. Climate influences will also have indirect impacts on energy costs as demands for renewable energy increase which could also put upward pressure on feed grain prices as bioenergy production competes for feed grains. The climate impacts on growth, reproductive success, and distribution of diseases may impact the ability to manage disease. This concern may be heightened in intensive production relative to nonintensive systems due to the density of animals. Future greenhouse gas (GHG) mitigation efforts may produce costs or revenue opportunities for the swine industry. Last, the role of reactive nitrogen (Nr) in climate and other intertwined issues could be very important. Swine producers will need to adapt to all these effects to maintain production levels.

2.09.2 GHG Emissions

US Environmental Protection Agency (US EPA) listed methane (CH_4) and nitrous oxide (N_2O) emissions from manure management among its 19 key categories which exert significant influence over the US total inventory. (CAST 2011). GHG losses from swine production occur in the barn, during treatment and storage of manure, and during and after land application of manure. US swine manure management systems are relatively high in GHG emissions because most swine manures are stored wet rather than dry (CAST 2011). Direct emissions of GHG from animal production in the United States have been estimated to be 203 Mt CO_2 Eq (carbon dioxide equivalents), or about 2.9% of the total US emissions (6957 Mt CO_2 Eq) in 2008 (CAST 2011). Swine production in Canada has been estimated to be 1835 kt CO_2 Eq or about 0.3% of total Canadian emissions (CAST 2011). The majority of the Canadian GHG emission estimate is derived from CO_2 from respiration (with 37.5% of CO_2 coming from manure degradation in the pig house) (CAST 2011).

Disparity between these livestock industry-related GHG contribution estimates and the 18% of total GHG contribution estimated by the FAO (2006) is caused by the inclusion in the UN FAO calculations of land use changes to produce feed grain and pasture for livestock. Whether or not deforestation to establish feed crop fields (or new pasture) should be included in the livestock industry's GHG emissions' estimate has been debated. For example, the recent CAST report (2011) points out that deforestation is not happening in the United States and therefore GHG emissions from deforestation should not be considered as part of the US livestock industries carbon footprint.

2.09.2.1 Nitrous Oxide Emissions

Estimates of N_2O emissions from swine barns in the United States range from 0.8 to 21 g N_2O day^{-1} AU^{-1} (AU = animal unit = the number of animals equaling 500 kg) (Cast 2011).

http://dx.doi.org/10.1016/B978-0-12-384703-4.00217-3

Estimates for N_2O losses from swine manure anaerobic lagoons in North America have been estimated at 20 g N_2O $year^{-1}$ $animal^{-1}$ (Cast 2011). Estimates of losses from anaerobic lagoons in North Carolina (USA) were reported as 0.3–0.4 kg N_2O day^{-1} ha^{-1} (Harper et al. 2004). (If one assumes the average anaerobic lagoon surface area of a 4000 head feeder to finish farm in North Carolina is approximately 3 acres (or 1.2 ha; Zehring et al. 2005), the Harper et al. (2004) estimate of N_2O emissions equals approximately 38 g N_2O $year^{-1}$ $animal^{-1}$.) Swine manure composted in deep bedded straw has been estimated to emit 58.9 g N_2O ton^{-1} of compost (CAST 2011).

Land application of liquid swine manure has been estimated by Harper et al. (2004) to emit 2.6–3.8 mg N_2O day^{-1} m^{-2} (versus 0.0016 mg N_2O day^{-1} m^{-2} before application). A yearly N_2O flux from land application of hog manure has been estimated at 61.3 mg N_2O m^{-2} (CAST 2011). (The Harper et al. (2004) daily estimate would equal the annual flux reported by CAST (2011) in less than 20 days.)

On a global basis, FAO (2006) estimated that swine production is responsible for 0.44 million tons of N_2O emissions per year with 25% (or 0.11 million tons $year^{-1}$) coming from industrial agriculture (**Table 1**). Swine production in North America, which is primarily intensified production (or industrial as labeled in **Table 1**), was estimated at 0.04 million tons of N_2O $year^{-1}$. Nitrous oxide emissions estimates in China and Western Europe are approximately 5 and 2 times higher, respectively, than that estimated for North America.

2.09.2.2 Methane Emissions

Methane emissions from swine barns have been estimated at 48–54 g CH_4 day^{-1} AU^{-1} (CAST 2011), and up to 160 g day^{-1} AU^{-1} for deep pit and pull plug finishing barns (CAST 2011). Estimates of lagoons emissions of CH_4 have varied widely from 0 to 188 g CH_4 day^{-1} AU^{-1} (CAST 2011). Measurements of average CH_4 emissions have been reported as 154 g CH_4 day^{-1} AU^{-1} (CAST 2011) and 21.4 g CH4 day^{-1} AU^{-1} (CAST 2011). Swine manure composted in deep bedded straw has been estimated to emit 254 g CH_4 ton^{-1} of compost (CAST 2011). Methane emissions from land application of liquid swine manure vary by time of application and method of application. Fall applications of swine manure have been estimated to emit twice as much CH_4 as springtime application (5.5 kg CH_4 ha^{-1}, 2.35 kg CH_4 ha^{-1}, respectively (CAST 2011)) with 98% of the emissions occurring in first 4 days.

Manure management in the United States emitted approximately 1.9 million tons of CH_4 in 2004 (**Table 2**). Swine manure management contributes the largest share of methane emissions relative to poultry and other livestock – almost half of which are from industrial swine production. Globally, nearly one-fourth of total CH_4 emissions are from industrial hog production (FAO 2006).

2.09.2.3 Carbon Dioxide Emissions

Global fertilizer production for feedcrops is estimated to be responsible for annual emissions of more than 40 million tons of CO_2 (**Table 3**). The emissions from fertilizer production for feed grains in the United States is about 29% of the total (11.7 million tons of CO_2), second only to China (14.3 million tons of CO_2).

CO_2 emissions induced by on-farm fossil fuels use for feed production may be 50% higher than that from feed-dedicated N fertilizer production; that is, 60 million tons of CO_2 globally (FAO 2006). Carbon dioxide emissions from on-farm energy use in Minnesota for swine are estimated at approximately 0.6 million tons $year^{-1}$ (**Table 4**). If this rate is used to estimate the

Table 1 Estimated total N_2O emissions from animal excreta in 2004

	N_2O emissions from manure management, after application/deposition on soil and direct emissions						
Region/country	*Dairy cattle*	*Other cattle*	*Buffalo*	*Sheep and goats*	*Pigs*	*Poultry*	*Total*
			(million tons $year^{-1}$)				
Sub-Saharan Africa	0.06	0.21	0.00	0.13	0.01	0.02	**0.43**
Asia excluding China and India	0.02	0.14	0.06	0.05	0.03	0.05	**0.36**
India	0.03	0.15	0.06	0.05	0.01	0.01	**0.32**
China	0.01	0.14	0.03	0.10	0.19	0.10	**0.58**
Central and South America	0.08	0.41	0.00	0.04	0.04	0.05	**0.61**
West Asia and North Africa	0.02	0.03	0.00	0.09	0.00	0.03	**0.17**
North America	0.03	0.20	0.00	0.00	0.04	0.04	**0.30**
Western Europe	0.06	0.14	0.00	0.07	0.07	0.03	**0.36**
Oceania and Japan	0.02	0.08	0.00	0.09	0.01	0.01	**0.21**
Eastern Europe and CIS	0.08	0.10	0.00	0.03	0.04	0.02	**0.28**
Other developed	0.00	0.03	0.00	0.02	0.00	0.00	**0.06**
Total	**0.41**	**1.64**	**0.17**	**0.68**	**0.44**	**0.36**	**3.69**
Livestock Production System							
Grazing	0.11	0.54	0.00	0.25	0.00	0.00	**0.90**
Mixed	0.30	1.02	0.17	0.43	0.33	0.27	**2.52**
Industrial	0.00	0.08	0.00	0.00	0.11	0.09	**0.27**

Adapted from FAO, 2006: *Livestock's Long Shadow: Environmental Issues and Options*. Food and Agricultural Orgainzation for the United Nations, Rome, Italy. ISBN 978-92-5-105571.

Table 2 Global methane emissions from manure management in 2004

	Emissions (million tons of CH_4 $year^{-1}$ by source)						
Region/country	*Dairy cattle*	*Other cattle*	*Buffalo*	*Sheep and goats*	*Pigs*	*Poultry*	*Total*
Sub-Saharan Africa	0.10	0.32	0.00	0.08	0.03	0.04	**0.57**
Asia[a]	0.31	0.08	0.09	0.03	0.50	0.13	**1.14**
India	0.20	0.34	0.19	0.04	0.17	0.01	**0.95**
China	0.08	0.11	0.05	0.05	3.43	0.14	**3.84**
Central and South America	0.10	0.36	0.00	0.02	0.74	0.19	**1.41**
West Asia and North Africa	0.06	0.09	0.01	0.05	0.00	0.11	**0.32**
North America	0.52	1.05	0.00	0.00	1.65	0.16	**3.39**
Western Europe	1.16	1.29	0.00	0.02	1.52	0.09	**4.08**
Oceania and Japan	0.08	0.11	0.00	0.03	0.10	0.03	**0.35**
Eastern Europe and CIS	0.46	0.65	0.00	0.01	0.19	0.06	**1.38**
Other developed	0.01	0.03	0.00	0.01	0.04	0.02	**0.11**
Global Total	**3.08**	**4.41**	**0.34**	**0.34**	**8.38**	**0.97**	**17.52**
Livestock Production System							
Grazing	0.15	0.50	0.00	0.12	0.00	0.00	**0.77**
Mixed	2.93	3.89	0.34	0.23	4.58	0.31	**12.27**
Industrial	0.00	0.02	0.00	0.00	3.80	0.67	**4.48**

[a] *Excludes China and India.*

Adapted from FAO, 2006: *Livestock's Long Shadow: Environmental Issues and Options*. Food and Agricultural Orgainzation for the United Nations, Rome, Italy. ISBN 978-92-5-105571.

Table 3 CO_2 emissions from the burning of fossil fuel to produce nitrogen fertilizer for feedcrops in selected countries

Country	*Absolute amount of chemical N fertilizer (1000 tons of N fertilizer)*	*Energy use per tons fertilizer (GJ $tons^{-1}$ of N fertilizer)*	*Emission factor (tons C TJ^{-1})*	*Emitted CO_2 (1000 tons $year^{-1}$)*
Argentina	126	40	17	314
Brazil	678	40	17	1690
Mexico	263	40	17	656
Turkey	262	40	17	653
China	2998	50	26	14 290
Spain	491	40	17	1224
UK[a]	887	40	17	2212
France[a]	1317	40	17	3284
Germany[a]	1247	40	17	3109
Canada	897	40	17	2237
USA	4697	40	17	11 711
Total	**14 million tons**			**41 million tons**

[a] *Includes a considerable amount of N fertilized grassland.*

Adapted from FAO, 2006: *Livestock's Long Shadow: Environmental Issues and Options*. Food and Agricultural Orgainzation for the United Nations, Rome, Italy. ISBN 978-92-5-105571.

Table 4 On-farm energy use for agriculture in Minnesota, United States

Commodity	*Minnesota ranking within US*	*Crop area (10^3 km^2) head (10^6) tons (10^6)*	*Diesel (1000 m^3 ~ 2.65–10^3 tons CO_2)*	*LPG (1000 m^3 ~ 2.30–10^3 tons CO_2)*	*Electricity (10^6 kWh ~ 288 tons CO_2)*	*Directly emitted CO_2 (10^3 tons)*
Corn	4	27.1	238	242	235	1255
Soybeans	3	23.5	166	16	160	523
Wheat	3	9.1	62	6.8	67	199
Dairy (tons)	5	4.3	47	38	367	318
Swine	3	4.85	59	23	230	275
Beef	12	0.95	17	6	46	72
Turkeys (tons)	2	40	14	76	50	226
Sugar beets	1	1.7	46	6	45	149
Sweet corn/peas	1	0.9	9	–	5	25

Note: Reported nine commodities dominate Minnesota's agricultural output and, by extension, the state's agricultural energy use. Related CO_2 emissions based on efficiency and emission factors from the United States' Common Reporting Format report submitted to the UNFCCC in 2005.

Adapted from FAO, 2006: *Livestock's Long Shadow: Environmental Issues and Options*. Food and Agricultural Orgainzation fo the United Nations, Rome, Italy. ISBN 978-92-5-105571.

CO_2 emissions by on-farm fossil fuel use for the US swine population of 65 million head in 2011 (USDA 2011), the overall CO_2 emission would be approximately 8 million tons year^{-1}.

2.09.3 Disease

Increased temperatures, more acidic conditions, and higher salinities for freshwater ecosystems have resulted in lower avian influenza survival in lab experiments (Vandegrift et al. 2010). Although these conditions suggest decreased survival of influenza viruses in the environment, predicting net impacts of climate conditions requires consideration of how viruses interact with other factors such as smaller, shallower wetlands, increased crowding, stress, and contact rates among migratory species and between wild and domestic birds and transmission to the swine population.

Some have predicted that the affects of disease under plausible future climate would be more pronounced in developing countries in humid and subhumid tropical climates (Zhao et al., 2005). However, the most recent episode of a novel H1N1 virus, which was widely reported to have first appeared on a swine farm in Mexico, a tropical developing country, quickly spread across the globe. Swine are recognized as mixing vessels in which swine, avian, and human influenza strains mix and match. Concerns have been expressed that widespread use of influenza vaccinations in intensive swine production may be 'pressuring change' in influenza evolution, helping to select for unique variants (Wuethrich 2003). Although the positive benefits of vaccinations are felt to outweigh the immunological pressure on influenza, if there are changes in enhanced influenza distribution in response to alterations in local and regional climate, the role the swine population plays in influenza evolutionary biology could become increasingly problematic.

2.09.4 Reactive Nitrogen Loss during Swine Production and Waste Management

Emissions of Nr have a complex effect on climate by altering global radiative forcing (Butterbach-Bahl et al. 2011). They directly affect the GHG balance through N_2O emissions and indirectly affect it by increasing tropospheric O_3 levels, altering methane fluxes and biospheric CO_2 sinks (including Nr deposition and O_3 effects) (Figure 1). Conversely, aerosol formed from NO_x and NH_3 emission (not shown in Figure 1) also has a cooling effect.

Modern agriculture uses large quantities of inorganic commercial N fertilizer to enhance crop productivity, currently supporting the production of about half the food consumed by the human population (Erisman et al. 2008). However, the flip side of the coin is that high levels of Nr are being released into the environment, causing numerous undesirable symptoms (e.g., algal blooms, hypoxic zones, eutrophication, ground water contamination, acid rain, atmospheric N deposition, overfertilization of terrestrial areas, increased tropospheric ozone, decreased stratospheric ozone, fine particulate matter, increased GHG) (US EPA 2011). As a result of the high mobility of Nr, agriculture is a leaky system when it comes to Nr. Much of the Nr released to the environment is from commercial inorganic N (Figure 2).

An Nr flow model for a Danish swine farm shows an example of quantities of the nitrogen introduced to the swine farm as feed, fertilizer, seed, and atmospheric deposition and its distribution into animal and crop products and losses as gases (NH_3, N_2, N_2O), and in soluble forms (DON, NO_3) (Figure 3). NH_3 emissions vary by housing type; animal size, age, and type; manure management, storage, and treatment; and weather variables, and can be expected to be higher in liquid-based systems which are more common in the United States than in Denmark. In their review, CAST (2011) reported that across a multistate (US) set of measurements and life cycle aspects, average NH_3 emissions were 48 and 30 g day^{-1} AU^{-1} for gestating and farrowing sows. Average NH_3 emissions for finishing barns ranged from 102 to 130 g day^{-1} AU^{-1} in deep-pit systems and 77–81 g day^{-1} AU^{-1} from pull plug barns. Specially formulated diets (low protein with synthetic amino acids) have been found to reduce NH_3 emissions by almost half.

Open air storage and treatment of hog manure in earthen anaerobic lagoons, typical in the southern and southeastern United States, can emit 5–40 g NH_3 day^{-1} m^{-2} (CAST 2011). Concrete storage pits are more common for swine manure in the Midwest United States with ammonia emission rates typically around 5–50 g NH_3 day^{-1} m^{-2}. (It should be noted that anaerobic lagoons have a much larger footprint than concrete storage pits.) Land application of liquid manure from a lagoon can result in large losses of NH_3 with levels greater than 100 g NH_3 day^{-1} m^{-2}. Manure land application using deep or shallow injection and drag shoe methods can decrease ammonia loss from 90+, 80+, and 60+%, respectively.

The first assessment of the overall effect of Nr emissions (between 1750 and 2005) on radiative forcing was conducted in Europe (Figure 4) (Butterback-Bahl et al. 2011). The main warming effects are from N_2O emissions (average of 17 mW m^{-2} with a range from 15 to 19 mW m^{-2}) and from reduction in the biospheric CO_2 sink by tropospheric O_3 effects on plants (average of 4.4 mW m^{-2} with a range of 2.3–6.6 mW m^{-2}). The main cooling effects are estimated to be from increasing the biospheric CO_2 sink through fertilization effects of atmospheric Nr deposition on N limited ecosystems (average (−)19 mW m^{-2} with a range of (−)30 to (−)8 mW m^{-2}) and by light scattering effects of Nr containing aerosols (average (−)16.5 with a range of (−)27.5 to (−)5.5 mW m^{-2}). Overall, European Nr emissions are estimated to have a net cooling effect, with uncertainty bounds ranging from substantial cooling to a small net warming (average (−)15.7 with a range of (−)46.7 to (+)15.4 mW m^{-2}).

The largest uncertainties concern the aerosols and Nr fertilization effects. In addition, published estimates suggest that the default N_2O emission factor of 1% used by the IPCC for indirect emissions from soil following Nr deposition is too low. Davidson (2009) estimated that 2–5% of manure and fertilizer Nr was emitted as N_2O as a result of microbial activities subsequent to land application. Crutzen et al. (2008) estimated 3–5% of newly produced Nr was emitted as N_2O.

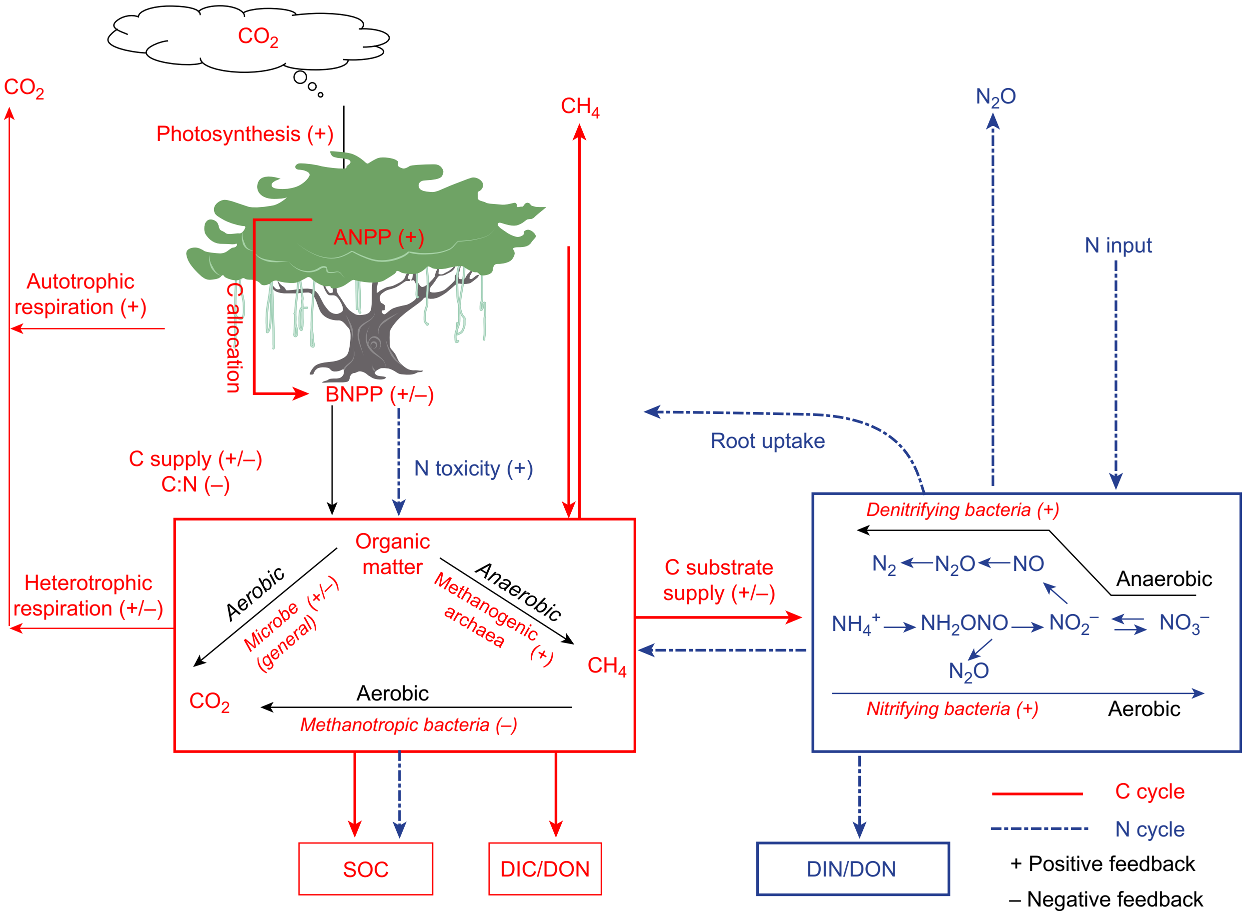
CO_2
CO_2
Photosynthesis (+)
CH_4
N_2O
ANPP (+)
Autotrophic respiration (+)
C allocation
N input
BNPP (+/–)
Root uptake
C supply (+/–)
C:N (–)
N toxicity (+)
Organic matter
Aerobic
Microbe (+/–) (general)
Anaerobic
Methanogenic archaea (+)
CH_4
Heterotrophic respiration (+/–)
CO_2
Aerobic
Methanotropic bacteria (–)
C substrate supply (+/–)
Denitrifying bacteria (+)
$N_2 \leftarrow N_2O \leftarrow NO$
Anaerobic
$NH_4^+ \rightarrow NH_2ONO \rightarrow NO_2^- \rightleftarrows NO_3^-$
N_2O
Nitrifying bacteria (+)
Aerobic
SOC
DIC/DON
DIN/DON
C cycle
N cycle
+ Positive feedback
– Negative feedback

Figure 1 Potential mechanisms regulating the terrestrial ecosystem responses of CO_2, CH_4, and N_2O production and consumption in increased availability of N. ANPP, aboveground net primary productivity; BNPP, belowground net primary productivity; SOC, soil organic carbon; DOC, dissolved organic carbon; DIC, dissolved inorganic carbon; DIN, dissolved inorganic nitrogen; DON, dissolved organic nitrogen. Butterbach-Bahl, K., and Coauthors, 2011: Nitrogen as a threat to the European greenhouse balance: *The European Nitrogen Assessment*, M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizzetti, Eds., Cambridge University Press.

Livestock production and manure management exert various influences on the environment and make up a relatively large share of the total emission of N_2O. Most effects deal with land use changes and nutrient element cycling. These have increased over the last decades particularly in response to the trends in livestock production to scale up in size, intensification, specialization, and conglomeration in regional clusters. These trends are facilitated by the availability of cheap energy, transport infrastructure, and cheap Nr fertilizer for boosting the production of animal feeds (Erisman et al. 2011).

Though livestock production consumes less than 3% of the global net primary productivity, its contributions to the global burden of NH_3, CH_4, and N_2O to the atmosphere range from 10 to 40% (Butterbach-Bahl et al. 2011). In addition, globally livestock excrete about 100 Tg Nr year^{-1}, but only 20–40% of this amount is recovered and applied to crops. The rest is lost to the environment, wherein it moves among soil, water, and air media in a process known as the nitrogen cascade, resulting in undesirable public health risks and environmental damage (Galloway et al. 2003; US EPA 2011).

Industrial production of Nr may be considered as having increased along with livestock and human populations (Butterbach-Bahl et al. 2011; Erisman et al. 2008). Expected substantial net warming effects of these wider Nr interactions remain to be quantified. Although individual components of the Nr emissions have cooling effects, there are many opportunities for 'smart management' linking N and C cycles (Butterbach-Bahl et al. 2011). These can help mitigate GHG emissions while reducing the other Nr related threats. Efforts need to focus on reducing the warming effects, while recognizing that the adverse effects of particulate matter and nitrogen deposition on human health and biodiversity may more than outweigh their climate benefits. (Sutton et al. 2011).

2.09.4.1 Estimates of Damages from Nr Emissions

Estimates of the monetary damage resulting from efforts to manage Nr losses have been calculated for Europe. Although these estimates consider impacts outside those associated with climate, these costs will likely add to, and be comingled with, the climate mitigation pressures experienced by swine and

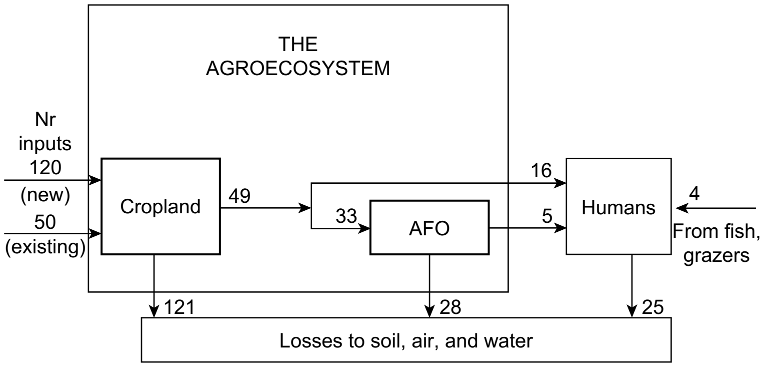
THE
AGROECOSYSTEM
Nr
inputs
120
(new)
50
(existing)
Cropland
49
33
AFO
16
5
Humans
4
From fish,
grazers
121
28
25
Losses to soil, air, and water

Figure 2 Major reactive nitrogen (Nr) flows in crop and animal production components of the global agroecosystem. Croplands create vegetable protein through primary production; animal production utilizes secondary production to create animal protein. Reactive nitrogen inputs represent new Nr, created through commercial processes and through cultivation-induced biological nitrogen fixation, and existing Nr that is reintroduced in the form of crop residues, manure, atmospheric deposition, irrigation water, and seeds. Portions of the Nr losses to soil, air, and water are reintroduced into the cropland component of the agroecosystem. Numbers represent teragrams of nitrogen per year. AFO, animal feeding operations. Galloway, J. N., J. D. Aber, J. W. Erisman, S. P. Seitzinger, R. W. Howarth, E. B. Cowling, B. J. Cosby, 2003: *BioScience*, **53,** 341–356.

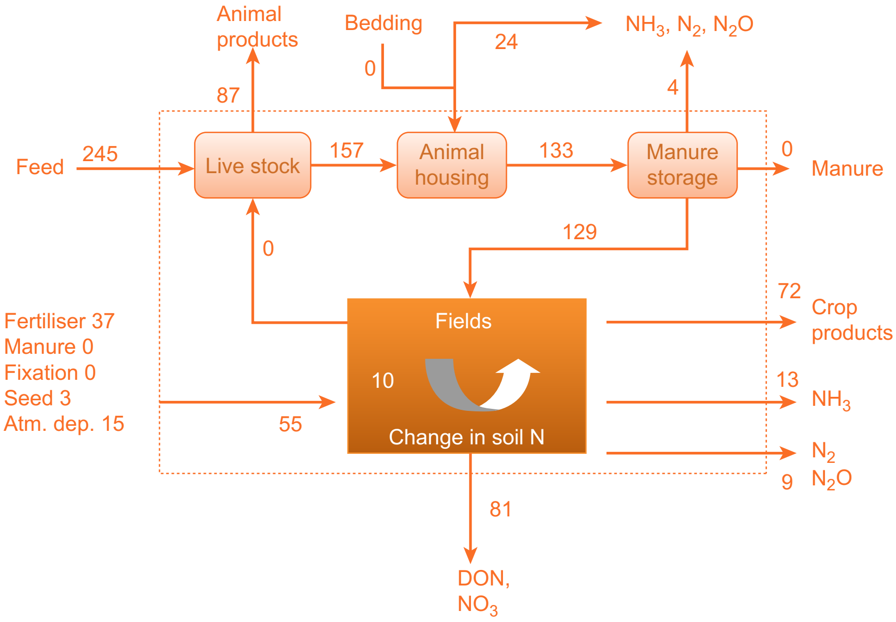
Animal
products
Bedding
0
24
NH_3, N_2, N_2O
87
4
Feed
245
Live stock
157
Animal
housing
133
Manure
storage
0
Manure
0
129
Fields
72
Crop
products
Fertiliser 37
Manure 0
Fixation 0
Seed 3
Atm. dep. 15
10
55
Change in soil N
13
NH_3
N_2
9
N_2O
81
DON,
NO_3

Figure 3 Annual nitrogen flows (kgN ha^{-1}) in a typical Danish swine farm. This example assumes no manure export. Jarvis, S., N. Hutchings, F. Brentrup, J. E. Olesen, K. ven de Hoek, 2011. Nitrogen flows in farming systems across Europe. *The European Nitrogen Assessment*, M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizzetti, Eds., Cambridge University Press.

other meat producers. European limits are already in place for land application of N in manure (170 kg ha^{-1}) for arable lands in Europe (Brink et al. 2011). These limits have increased costs for the pig and poultry sector by €10 ton^{-1}, amounting to a national cost of €90 million in 2006. About half of these costs are related to additional costs for remunerations to farmers for accepting the manure (transfer costs are not considered for national assessments) (Brink et al. 2011).

Estimates of the total annual damage in the 27 countries in the EU as a result of emissions of N_2O, NO_x, and NH_3 to air and water in 2000 from all sources, ranged from €70 to 320 billion. This corresponds to a welfare loss of €150–750 per capita, which is equivalent to 0.8–3.9% of the average disposable per capital income in 2000. About 60% of the damage costs are related to human health, 35% to ecosystem health, and 5% to the effect on GHG balance (Figure 5).

Figure 5 and Table 5 show that the unit damage costs for N_2O are small compared with other costs items, implying that N policies for agriculture should not focus on reduction of emission of N_2O alone. However, when part of the N addition is in the form of manure, the difference between externalities and net crop benefits will increase in view of the higher emission factors for ammonia (up to 70%) and the lower fertilizing efficiency of N in manure as compared with chemical fertilizer. In view of the high unit damage cost for ammonia, the use of manure without applying far-reaching low emission

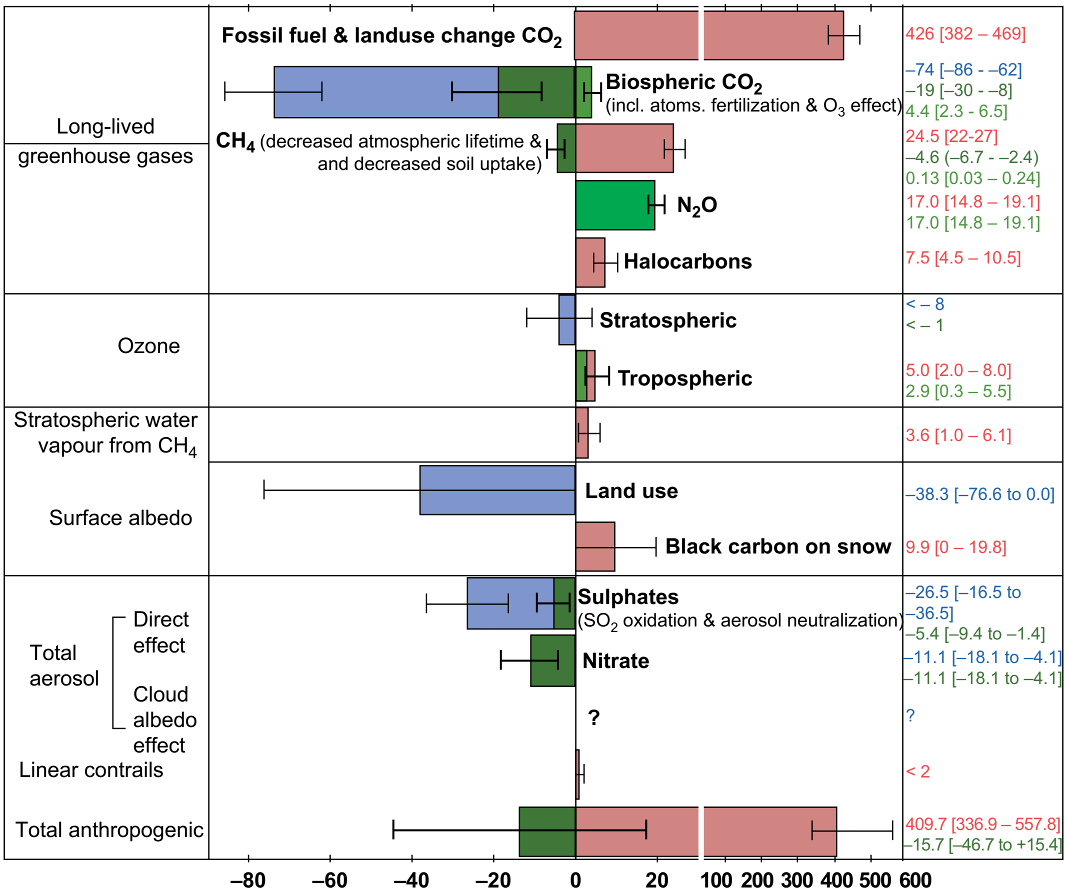

Figure 4 European contribution to global radiative forcing (mW m^{-2}). Butterbach-Bahl, K., and Coauthors, 2011: Nitrogen as a threat to the European greenhouse balance: *The European Nitrogen Assessment*, M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizzetti, Eds., Cambridge University Press.

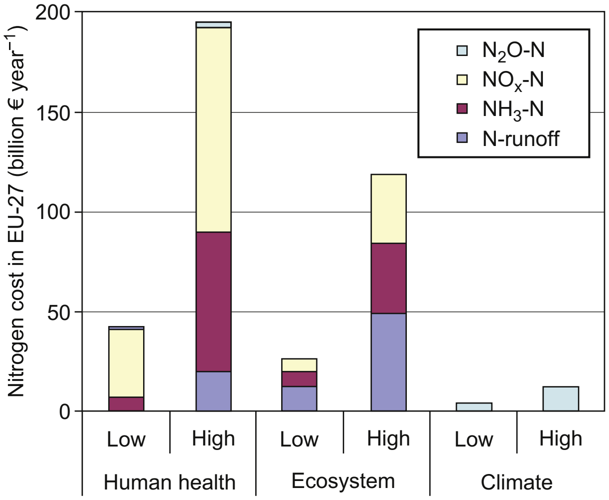

Figure 5 Low and high estimates of the total social damage in EU 27 as a result of environmental N-emissions in 2000. Brink, C., and Coauthors, 2011: Cost and benefits of nitrogen in the environment. *The European Nitrogen Assessment*, M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizzetti, Eds., Cambridge University Press.

techniques therefore would often be not beneficial for society. Stricter regulation of manure application and improved N efficiency would provide robust benefits for society.

Annual marginal social costs of N damages are between 20 and €150 billion, as compared with annual benefits of N fertilizer for farmers between €10 and 50 billion or €20 and 80 billion when including long-term benefits of secure soil N availability (Brink et al. 2011). These results suggest that at the present level of N fertilization, the marginal environmental costs tend to be close to the marginal agricultural benefit. As Nr emissions and social impacts increase proportionally with the use of N fertilizer, and effects on crop yield levels off, the risk of externalities exceeding crop benefits will tend to increase with higher inputs. However, it should be stressed that the upper bounds of the environmental costs are theoretical and have lower probability of occurrence than the empirically based upper bounds of the agronomic benefits.

So whether the drive to reduce Nr losses from swine production is propelled by climate concerns, public health risks, environmental damage, or some combination of all of these, pressure on swine producers to better manage Nr and prevent loss to air, water, and soil will increase. The intertwined trends in GHG emissions, population growth, and concern

Table 5 Emissions of Nr in EU 27 and estimated ranges of unit damage costs for the major Nr pollutants and, between parentheses, single values inferred from studies used in this assessment

	Emission-EU27		*Health*	*Ecosystem*	*Climate*	*Total*
	Tg Nr	*% agric*	*€ kg^{-1} Nr*	*€ kg^{-1} Nr*	*€ kg^{-1} Nr*	*€ kg^{-1} Nr*
Nr to water	4.9	60	0–4 (1)	5–20 (12)		5–24 (13)
NH_3–N to air	3.5	80	2–20 (12)	2–10 (2)		4–30 (14)
NO_x–N to air	3.4	10	10–30 (18)	2–10 (2)		12–40 (20)
N_2O–N to air	0.8	40	1–3 (2)		5–15 (9)	6–18 (11)

Adapted from Brink, C., and Coauthors, 2011: Cost and benefits of nitrogen in the environment. *The European Nitrogen Assessment*, M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizzetti, Eds., Cambridge University Press.

over public health and environmental risks are difficult to unravel (Table 6). However, opportunities to receive compensation for reduction in Nr losses might be best achieved by GHG emission reduction by way of offset credits. Thus elucidation of the role of Nr emissions in climate might be of benefit to the industry.

2.09.5 Diet Implications

If the impacts of climate become more apparent, the call for action among the common citizen, their elected representatives and regulatory agencies will likely get more urgent. This scenario presents a further risk to swine production as the full suite of climate impacts related to dietary choices would likely also come under scrutiny. As detailed above, not only are the direct emissions of CH_4 and N_2O from meat production and manure management involved in the accumulation of GHG, but the indirect role of Nr in climate and other undesirable effects on public health and environment are also of concern. The amount of Nr lost to the environment during the production of protein in milk, egg, and poultry is much less than in pork and especially beef, indicating a shift from beef to pork to poultry, and milk would also decrease the Nr use (Tables 7–9).

In a recent review by Winiwarter et al. (2011), several studies of human diet were discussed. In one study, three meal options with similar energy and protein contents were evaluated. GHG emissions varied from 0.42 (soybean) through 1.3 (pork) to 4.7 (beef) kg CO_2 eq. Another study compared four diets and included a 'healthy diet' based on sparing consumption of meat (daily intake of 10 g beef, 10 g pork, 46.6 g chicken meat and eggs, and 23.5 g fish per capita) (Table 10). Using annual meat production and shares of domestic production, the average intake of meat products and eggs per capita in the EU was compared with consumption in the case of the healthy diet. The reduction in consumption of pork relative to the healthy diet is highest at 87%. The total potential reduction in meat and egg consumption is 63%. As the milk demand is kept stable, there is no reduction in the number of dairy cattle. The number of cattle, pigs, and poultry can be reduced because of the decreased demand for their products. Simple calculations show that N excretion in the EU could decrease by about 44% and the ammonia emission by about 48%. The potential decrease in ammonia emissions is somewhat higher because the number of housed animals (which contribute more strongly to NH_3 emissions) decreases whereas the number of grazed animals remains constant. In essence, low meat diets may result in lower GHG emission and lower ammonia emissions (Table 10). Efforts to lower the Nr loss

Table 6 Quantifiable targets to avoid deterioration due to nitrogen

Environmental problem	*Nitrogen connection*	*Target*
Loss of ecosystems services due to: • Acidification • Eutrophication • Biodiversity loss	Atmospheric deposition of nitrate and/or ammonia	Critical loads (exceedance of soil specific values)
Adverse impact on plant species composition	Atmospheric concentration of ammonia	Critical levels (exceedance of critical NH_3 concentrations)
Crop damage	O_3 formation (NO_x chemistry)	Accumulated exposure over threshold
Human health	NO_x concentration	Years of life lost
	O_3 formation (NO_x chemistry)	Disablement Adjusted Life Years
	PM formation (NO_x chemistry and ammonia)	Quality standard (concentrations)
	Nitrates in drinking water	
Climate change	N_2O emissions CO_2 emissions/uptake, as the natural C cycle is influenced by N in the environment O_3 formation (NO_x chemistry)	Global mean temperature (limit: 2 °C increase above preindustrial)

Adapted from Winiwarter, W., and Coauthors, 2011: Future scenarios of nitrogen in Europe. *The European Nitrogen Assessment.* M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizzetti, Eds., Cambridge University Press.

Table 7 Summary of annual N in products and losses (kg ha^{-1}) derived from typical farm nitrogen budgets with losses also expressed per unit N in products

Farm management	*Nitrogen in crop and animal products (kg ha^{-1} year^{-1} N)*	*Nitrogen losses (kg ha^{-1} year^{-1} N)*	*N losses per unit N in products (as ratio)*
Arable	99	84	0.85
Pig	159	131	0.82
Beef	40	108	2.7
Dairy (conventional)	56	143	2.55
Dairy (organic)	39	75	1.92

Adapted from Jarvis, S., N. Hutchings, F. Brentrup, J. E. Olesen, and K. ven de Hoek, 2011: Nitrogen flows in farming systems across Europe. *The European Nitrogen Assessment*. M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizzetti, Eds., Cambridge University Press.

Table 8 Total excretion of Nr by livestock and emission of N_2O (kilotons) from animal manure management systems in EU 27 in 2000

Livestock category	*Nr excreted*	*Housing and storage N_2O^a*	*Land application N_2O*	*Grazing N_2O*	*Total N_2O*
Dairy cattle	2670	18	18	12	48
Other cattle	3210	18	14	27	59
Pigs	1687	9	17		26
Poultry	1750	7	9		16
Other	1055	2	3	24	29
Total	10 372	54	61	62	177

[a] *N_2O emissions given here are the sum of emissions from housing systems and storage and do not include losses from mineral fertilizer applications to soil.*

Adapted from Butterbach-Bahl, K., and Coauthors, 2011: Nitrogen as a threat to the European greenhouse balance: *The European Nitrogen Assessment*, M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizzetti, Eds., Cambridge University Press.

Table 9 Non-CO_2 GHG emissions associated with the production of various food items. Units are 10^6 CO_2 eq year^{-1}, except column 6

	CH_4				
Food	*Enteric fermentation*	*Manure management*	*N_2O manure management*	*Sum*	*Approx percentage of total*
Eggs	–	2.08	0.62	2.70	1
Dairy	26.68	18.18	21.96	66.82	29
Beef	82.04	4.43	34.34	120.81	56
Pork	2.07	30.20	1.70	33.97	15
Poultry	–	2.31	0.68	2.99	1
Sheep	1.16	0.03	0.60	1.79	1
Goats	0.14	0.01	0.20	0.35	<1
				Total: 229.41	

Adapted from Eshel, G., P. A. Martin, 2006: Diet, energy, and global warming. *Earth Interact.*, **10,** 1–17.

Table 10 Meat/egg production and consumption, 2007, in the EU countries

Activity	*Meat/egg production (10^6 ton year^{-1})*	*Share of domestic production*	*2007 diet (kg cap^{-1} year^{-1})*	*Healthy diet (kg cap^{-1} year^{-1})*	*Reduction in intake*
Ruminants[a]	9.3	96%	19.8	6.24	68%
Pigs	22.9	108%	44.8	5.66	87%
Poultry	11.4	103%	23.1	25.3	32%
Eggs	7.0		14.1		
Total meat + eggs	50.6		101.8	37.2	63%

[a] *Ruminants are cattle, sheep, and goats.*

Adapted from Winiwarter, W., and Coauthors, 2011: Future scenarios of nitrogen in Europe. *The European Nitrogen Assessment*, M. A. Sutton, C. M. Howard, J. W. Erisman, G. Billen, A. Bleeker, P. Grenfelt, H. van Grinsven, and B. Grizzetti, Eds., Cambridge University Press; FEFAC 2008; healthy diet: Stehfest et al. 2009.

from swine operations could help reduce the GHG impacts of diets containing pork products.

2.09.6 Mitigation Opportunities

Given the array of undesirable impacts of swine production associate with GHG and Nr emissions, the industry would be well served to diligently explore opportunities to reduce such emissions. Perhaps one of the most straightforward mitigation opportunities lies in the capture of CH_4 emissions from manure storage/treatment systems using anaerobic digesters. The best use of the CH_4 captured by anaerobic digesters is renewable energy production, either electrical, heat, or both (i.e., cogeneration). In addition to energy, GHG offset credits could potentially also be sold on the voluntary or regulatory market. Even if the CH_4 is flared, given that CH_4 has a global warming potential (GWP) of 21 (IPCC 2007), the CO_2 emitted (with a GWP of 1) results in much lower radiative forcing. Currently the economics of anaerobic digestion are challenging. Registration and verification processes for GHG credit sales add additional hurdles. In addition, management of anaerobic digester effluent is also needed to prevent loss of NH_3. However, NH_3 emission controls also offer the potential for additional revenue from N water pollution offset credits or capture for sale as fertilizer (Rudek and Aneja 2011). Given the benefits to society of reducing commercial fertilizer use (e.g., less energy use, less Nr emissions) by recycling NH_3 captured from manure into a concentrated product that can be efficiently transported, a cogent argument can be made that incentive payments along the lines of those provided for biodiesel production would be in society's interest.

More widespread and efficient use of the Nr in manure is also needed to reduce undesirable impacts. Long-term changes could include a shift of the industry to areas that can use additional manure for crop fertilization. Once NH_3 losses are controlled, much more Nr will need to be managed. Many swine operations will not have the addition farm land or crop needs to absorb the additional Nr. Options for managing the additional Nr include denitrification, NH_3 capture and concentration, or production of a manure value-added product (e.g., compost, vermicompost). Care will need to be taken that denitrification treatment systems are optimized to avoid high levels of N_2O byproducts. With GWP of about 310 (IPCC 2007), even small percentages of N_2O can quickly add up to large increases in radiative forcing.

The swine industry has been effective in increasing the feed conversion efficiency, providing financial benefits in reduced feed costs, which could become increasingly important if feed grain prices increase. Modifications in swine diets could also help in reducing Nr concentrations in manure and hence Nr losses.

Adapting to possible increased precipitation and more severe storms translates into reducing the risk of upset of treatment systems and barn flooding. Excluding rainfall from manure treatment systems and moving barns and manure treatment systems out of flood plains seem the most reasonable modifications to minimize threats from precipitation pattern changes. Again anaerobic digesters may be the most prudent treatment system to adopt to exclude rainfall.

The potential for intensive swine production to become a source of novel influenza viruses as a result of alterations in climate patterns and increased density of swine production suggests that it would be prudent for both the swine industry and the society to increase its surveillance of novel influenza strains appearing in the swine herd.

2.09.7 Conclusion

Modern agriculture provides food for an increasing number of humans through intensive agriculture. To achieve this feat, agriculture has gone through major changes over the last few decades becoming increasingly intensified. Massive use of industrial fertilizers has improved crop yields, and efficient concentrated animal feeding operations (CAFOs) dominate the production of swine both in the United States and abroad. However, on a global basis, agriculture is now recognized as a major force pushing the environment beyond its 'planetary boundaries' (Rockstrom et al. 2009). Clearly something must be done to reform agriculture and particularly livestock production, to reduce its contributions to air, water, and soil pollution, and increasingly human health and climate concerns.

Wendell Barry is famously quoted as saying, "The genius of American farm experts is very well demonstrated here: they can take a solution and divide it neatly into two problems" (Barry 1996). If reduced meat consumption, often cited as one of the solutions from reducing agriculture's negative environmental impacts (see for example Foley et al. 2011), is not to be the only solution to reducing environmental impacts, modern livestock producers must show that its genius can be applied to greatly reducing the massive footprint of livestock agriculture. As Barry implies, capturing the resources inherent in manure must be part of the solution.

Agriculture (both animal and crop) do not have to be a source of human health, climate, air, water, and soil quality problems; they can and should be a source of solutions. Society must invest in the research needed to find solutions. However, it is also critical that farmers and livestock producers come to the table to join, and ultimately lead, the search for solutions.

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2.10 Vulnerability of Mediterranean Agricultural Systems to Climate: From Regional to Field Scale Analysis

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2.10.1 Introduction

The fourth Intergovernmental Panel on Climate Change (IPCC) report intimated that global climate change has been observed in recent decades. In particular, this change has been characterized by a temperature increase of 0.74 °C (0.56–0.92) over the period 1906–2005 (Meehl et al. 2007). This trend could continue in the coming decades with an unequal distribution across the globe causing a high level of variability, primarily in terms of precipitation and temperature. The Mediterranean basin is one of the regions most vulnerable to plausible alterations in climate (Ewert et al. 2005).

As a sector that is highly dependent on climate and natural resources (water and soil), Mediterranean agriculture is one of the economic sectors under the most serious threat (Iglesias 2008). Changes in climate conditions would have direct consequences on the development of plants (Seguin 2007; Gracia De Cortazar Atauri et al. 2008), agricultural production (Iglesias 2008; Gommes and Balaghi 2009; Reidsma et al. 2010), farmers' incomes (Chabchoub et al. 2010), and natural resources, in particular water (Fischer et al. 2007; Iglesias et al. 2011).

The behavior of agricultural systems to increased variability in temperature and precipitation would not be the same everywhere. This can be explained by the effects of climate on crop yields (Iglesias and Minguez 1997). Vulnerability to climate varies as it is primarily linked to the characteristics specific to each type of agriculture (Anphoux et al. 2003). For instance, an increase in water stress resulting from a reduction in precipitation and an increase in temperatures would probably cause a 16% fall in wheat yields in southern Europe (Olesen and Bindi 2002), while this figure could reach 50% on the southern shores of the Mediterranean (Meehl et al. 2007).

These changing crop yields would be reflected in the instability of farmers' incomes (Reynaud 2008) and disputed responses at both regional and farm levels (Nardone et al. 2010; Reidsma et al. 2010).

The response of the different farms to the variability of precipitation and temperature depends on several biophysical, economic, and institutional factors. From a biophysical point of view, the choice of crop system in relation to the type of soil and climate is a key element at the farm level with regard to increasing the resilience of cereal crops. According to Asseng et al. (2008), reserving cereals (in particular durum wheat) for deep soils with a good useful water reserve is a strategy for reducing the vulnerability of wheat to water stress that is increasingly common during the spring (Asseng et al. 2008). Nevertheless, this strategy may prove insufficient during particularly dry seasons or for irrigated crops such as maize. In such a context, a farmer's investment capacity to install efficient supplemental irrigation systems adapted to the availability and quality of irrigation water is indispensable to offset the yields lost due to climate. Furthermore, two main issues should be considered in assessing resilience and long-term adaptive capacity:

- Short-term objectives aimed at improving resilience are often in conflict with long-term objectives aimed at increasing the long-term adaptive capacity of the farm. For example, the use of drip irrigation to increase water efficiency and combat drought, as seen in various cereal-based systems in the southern part of the Mediterranean region, may gradually increase the concentration of soil salt, thereby reducing the long-term adaptive capacity of the farming system (Belhouchette et al. 2012).
- In many regions, such as the northern Mediterranean, farms have become specialized in either specific livestock or arable farming. These specialized farms, especially dairy farms and arable farms, will probably respond more to climate change than mixed or diversified farms, that is, farms with both livestock and arable production that have more options for change and thus a greater resilience to environmental change.

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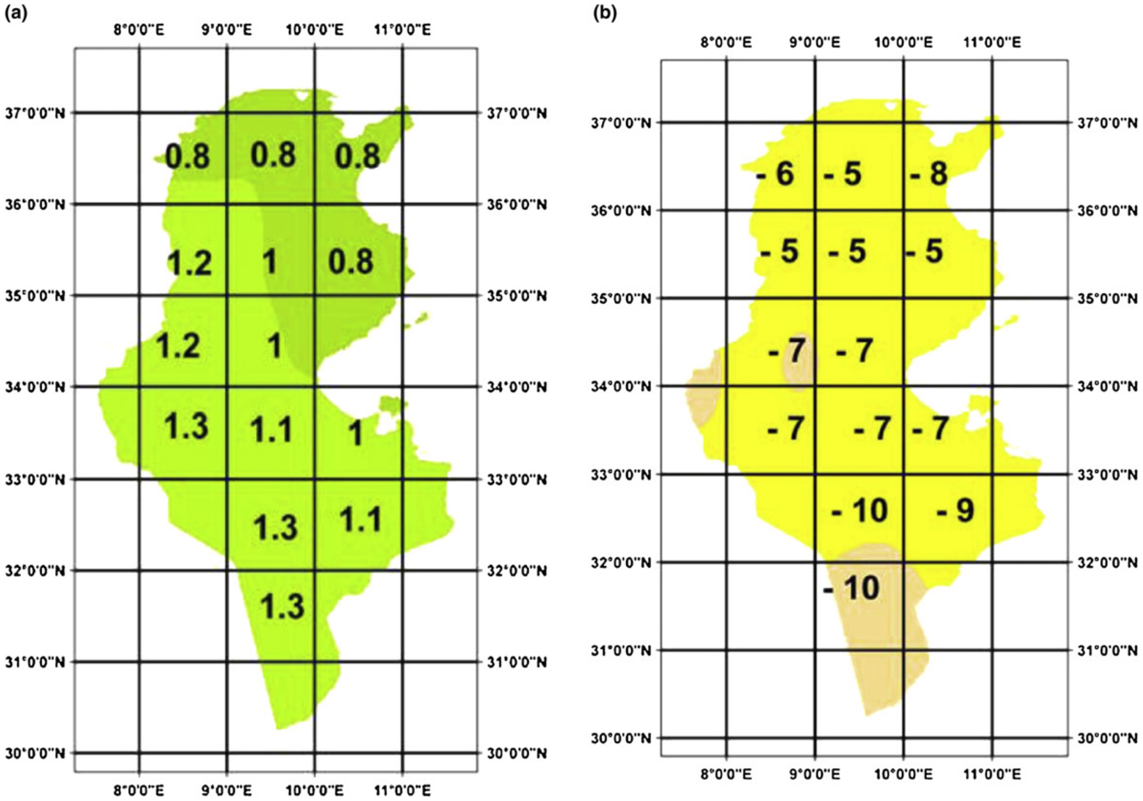

Figure 1 One plausible scenario of (a) increases in annual average temperatures and (b) falls in annual precipitation in Tunisia by 2020. GTZ, 2007: Stratégie nationale d'adaptation de l'agriculture tunisienne et des écosystèmes aux changements climatiques. Cahier 2: synthèse, 13 pp.

Understanding how Mediterranean farms operate in a context of climate means forecasting the change in the farm's environment, in particular in terms of water and soil resources, and assessing the responses of the crop systems to water and heat stress that could become more frequent. Calling on a broad review of the literature, this chapter aims to describe the possible behavior of natural resources, farms and crops systems in light of climate uncertainty. A more detailed analysis will systematically be presented using the case of Tunisia as an example.

2.10.2 Climate in the Mediterranean Region

Located in the southern Mediterranean, Tunisia enjoys a predominantly semiarid and arid climate (Labane 2002). The average annual temperature is between 16 and 22 °C, with a variability between winter and summer (average annual temperatures between 6 and 12 °C and 26 and 32 °C, respectively). (MSP/MEDD 2010).

Figure 1 (GTZ 2007) illustrates one plausible scenario of increases in average temperatures in Tunisia by 2020. Using this map, three average temperature increase zones can be identified: the first zone concerns the north, Cap Bon, and the center-east of the country, with an increase of +0.8 °C; the second is covered by the center of the country with an increase of +1.1 °C; and the third includes southwest and extreme south of the country demonstrating a larger temperature increase (+1.3 °C). The rise in temperature will be more marked by 2050, in particular in the south of the country that will experience a temperature increase of +2.7 °C (GTZ 2007).

2.10.3 The Impacts on Water and Soil Resources

Water resources in the Mediterranean region are already limited in comparison to other countries of the world. The "volume of renewable water resources of all countries of the Mediterranean basin is estimated at 1080 $\mathrm{km}^3\,\mathrm{year}^{-1}$, that is, less than 3% of global resources for more than 7% of the global population" (Milano 2010). Furthermore, a major disparity exists between the countries on the two shores of the Mediterranean due both to the difference in climates and to an uneven distribution of water resources. The northern Mediterranean countries account for 68% of all water resources within the basin compared to 23% in the countries on the southern shores and 9% in the eastern Mediterranean countries (Milano 2010).

Figure 2 illustrates the changing indices for the use of renewable natural resources (defined as the ratio of the annual volume of renewable natural water resources used to the average annual volume of available renewable natural water resources expressed as a percentage) between 2005 and 2025 for all Mediterranean countries. The most serious tension concerning water resources can be observed in the countries of

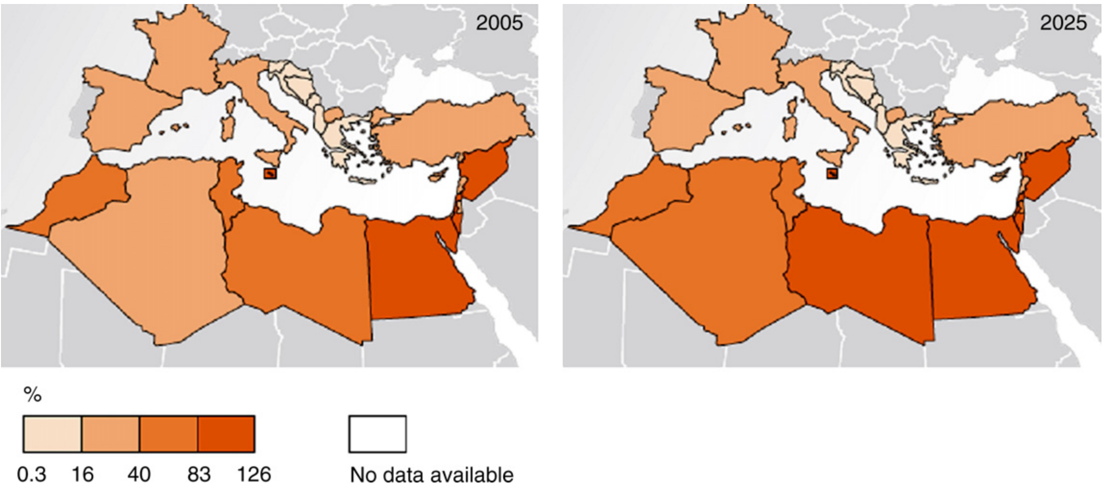

Figure 2 Evolution of the indices for the use of renewable natural water resources in Mediterranean countries (whole countries) for the years 2005 and 2025. An index close to or greater than 75% indicates significant tension concerning water resources, a ratio of between 50 and 75% demonstrates a high risk of medium-term structural tension, while a ratio of between 25 and 50% means that the countries may experience local or cyclical tensions. Pintus, 2009: *Preserving natural resources*. Rethinking rural development in the Mediterranean. CIHEAM. Presses de Sciences Po, 27–57. Using the Blue Plan database.

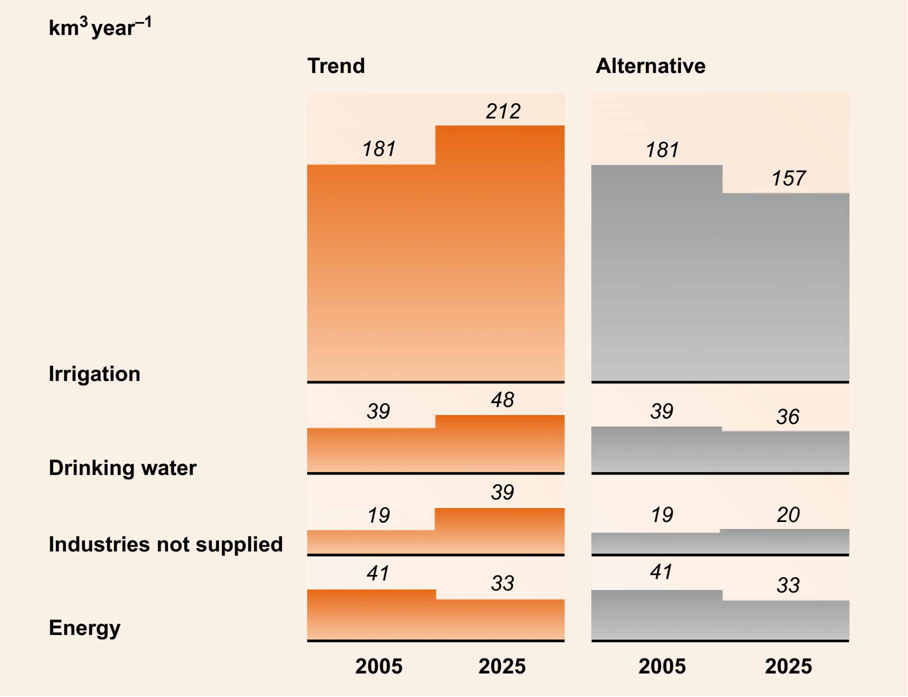

Figure 3 The evolution of water use per sector in the Mediterranean basin for the trend and alternative scenarios between 2005 and 2025. The trend scenario predicts a major increase in problems, whereas the alternative scenario aims at a more sustainable development in relation to the water resource management policies. Pintus, 2009: *Preserving natural resources*. Rethinking rural development in the Mediterranean. CIHEAM. Presses de Sciences Po, 27–57. Using the Blue Plan database.

the southern and eastern Mediterranean, with an index exceeding 50%. Climate effects can exacerbate regional disparities in terms of water resources (Meehl et al. 2007). Alterations in climatic conditions could accelerate the hydrological cycle including changes in precipitation, evapotranspiration, runoff, and the intensity and frequency of floods and droughts (Watson et al. 1996). In Spain, for example, as a result of a plausible temperature increase (+0.4 °C in winter and +0.7 °C in summer) and a reduction in precipitation, a 17% reduction in the availability of water at the national level is forecast. The effects of these changes would be even greater in southern Spain with a fall of up to 34% (Iglesias et al. 2007).

This climate pressure is compounded by:

- An estimated 18% increase in the demand for renewable water resources by 2025 (Antipolis 2008);
- A constantly increasing population, in particular, in the countries of the southern and eastern Mediterranean. It is estimated that the population will increase by 100 million people to reach 340 million inhabitants by 2025 (Benblidia and Margat 2008);
- Increased competition for water resources among the different users, in particular, during the summer when demand is high and resources scarce, notably in the southern and eastern Mediterranean. Figure 2 illustrates the estimated water use per sector in two different scenarios (trend and alternative) for the year 2025.

In the Mediterranean, agriculture is one of the sectors that consumes the most water. The use of water in agriculture exceeds 60% in Algeria, Tunisia, Mauritania, Spain, Greece, and so on, compared to 15% total use in France (Milano 2010). According to Fischer et al. (2007), water requirements for irrigation purposes would increase in the wake of both socioeconomic development and plausible climatic conditions over the coming decades.

Tunisia is considered a water-poor country with a ratio of 480 m^3 $inhab^{-1}$ $year^{-1}$ (below the water poverty threshold of 500 m^3 $inhab^{-1}$ $year^{-1}$). This ratio will fall to 360 m^3 by 2030 when the population will have risen to 13 million inhabitants (Louati 2011).

Water resources available in Tunisia are divided between surface water (51%) and underground water (49%). These resources are unevenly distributed across the country. Table 1 illustrates the regional distribution of potential water resources in Tunisia for 2008. Surface water resources diminish as we travel from north to south. The majority of surface water comes from the northern basins (Medjerda), which provide a relatively large and regular supply; while the central and southern regions of the country boast a large potential of underground resources (groundwater and deep water), which, nevertheless, demonstrate a low renewal level and a high level of salinity (Mekki 2010). A total of 87% of groundwater has a salinity of over 3 g l^{-1} (Lahache 2007).

Using the future strategic orientations for the water sector, it has been possible to compare demand and supply in 2020, 2030, 2040, and 2050 under a subset of plausible future conditions (MARH 1998; GTZ 2007). Figure 4 illustrates scenarios of the resources/demand for resources balance. Thanks to the resource mobilization efforts accompanied by recourse to nonconventional resources and a water-saving policy, the study has shown that the resources/demand balance would remain in surplus in 2040 for an average scenario. From 2050, the situation would become more critical, if these scenarios are correct, particularly in central and southern Tunisia, as water requirements will be more or less equal to the resources available. Moreover, government strategies may be sustainable in the medium term but not in the long-term under this set of plausible future conditions.

Table 1 Regional distribution of potential water resources in Tunisia in millions of m^3

		Underground water		
	Surface water	*Ground water*	*Deep water*	*Total*
North	2185	388	285	2858
Center	290	237	220	747
South	225	115	885	1235
Total	2700	740	1400	4840

MARH, 1998: Eau 21: stratégies à long terme du secteur de l'eau en Tunisie (2030). *Direction des ressources en eau de Tunis.*

Climate (temperature and precipitation) effects for Tunisia, if there is a warming and drying, would increase the water vulnerability of the country with disparities between the north, the center, and the south of the country. Surface and underground water could plausibly diminish by 5 and 28%, respectively, by 2030, leading to a reduction in water available for use. In the event of a lack of water, the agricultural sector will be the first to be affected by the shortage as agricultural needs represent 81% of resources. This lack of water could total 50% of needs (Lahache 2007).

In northern Tunisia, a 9.3% increase in evaporation would probably lead to a fall in water supplies in reservoirs of approximately 1%. Changes in seasonal precipitation could lead to less frequent silt clearance and thus to a 5% reduction in storage capacity by 2030. In central and southern Tunisia, the increased needs of the agricultural sector resulting from an increase in temperature and a reduction in precipitation would lead to the overuse of underground water resources as well as deterioration in the quality of the water (Lahache 2007).

The deterioration in the quality of irrigation water coupled with reduced precipitation and increased evaporation of water in the spring and early summer would result in a low level of soil humidity in summer and, thus, an increased risk of drought as well as an increase in soil salinity. The Mediterranean region is vulnerable to soil salinity, in particular in the southern and eastern regions (Figure 5).

In regions where the climate is arid or semiarid, soil salinity is essentially linked to irrigation (Pintus 2009). The problem of soil salinity primarily concerns irrigated areas. For instance, the salinity observed in 1995 in the irrigated areas of the lower Medjerda Valley (northern Tunisia) shows that 28% of the soils exceed the critical level of salinity of 4 ds m^{-1}. This problem of increased soil salinity is exacerbated by the absence of drainage networks and the use of irrigation techniques, which are often not suited to the type of soil or the crop cultivated, thereby causing an accumulation of salt around the roots of plants and thus a significant fall in yield, in particular for the crops most sensitive to salinity (market gardening, maize, etc.) (Abbes 2004). Table 2 illustrates the yield of two crops relatively sensitive to soil salinity (maize and tomatoes according to two different types of soil in terms of both the texture and salinity of the soil). Soil salinity causes a fall in maize and tomato yields of 21 and 47%, respectively.

If the regional climate changes, an increase in soil salinity caused by reduced precipitation and more frequent droughts could occur. In his study on the assessment of the sustainability of Mediterranean production systems, Belhouchette (2004) demonstrated that the drier the climate, the greater the soil salinity. Furthermore, soil salinity is higher when precipitation

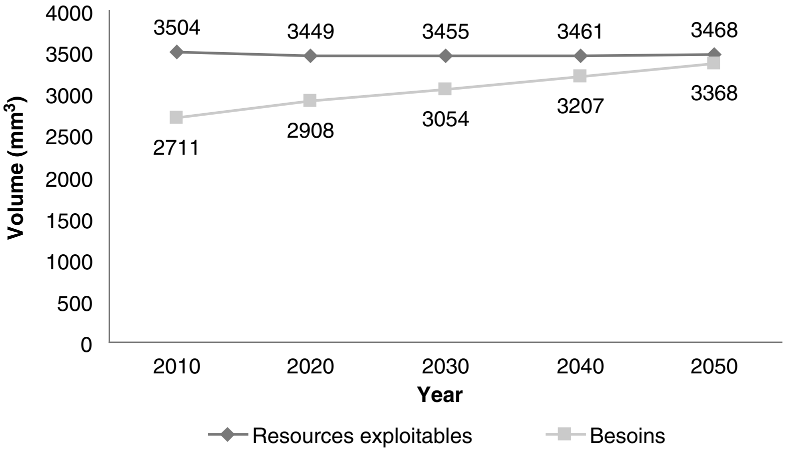

Figure 4 Forecast available/required water resources balance in 2050, ignoring the effects of climate change, in a scenario of average resources available and average needs. GTZ, 2007: Stratégie nationale d'adaptation de l'agriculture tunisienne et des écosystèmes aux changements climatiques. Cahier 2: Synthèse, 13 pp.

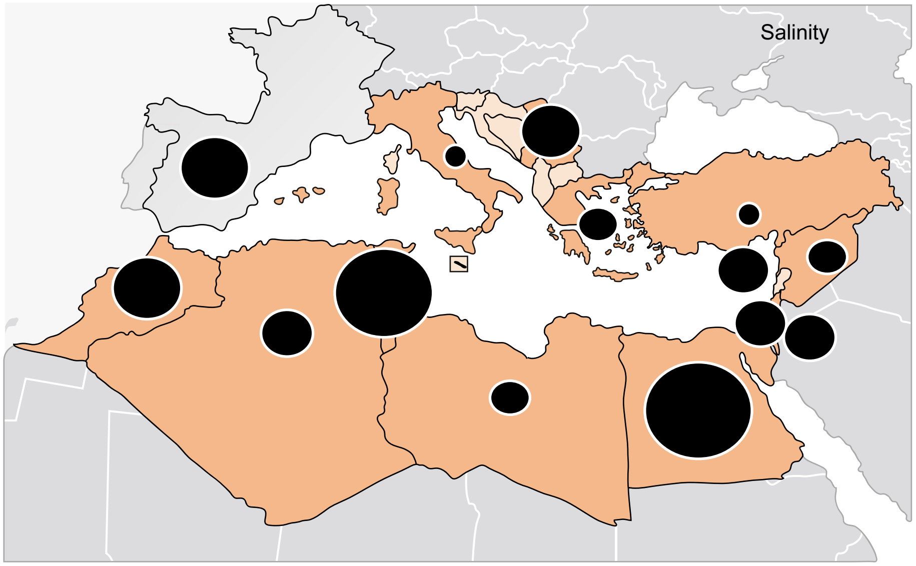

Figure 5 Soil salinity in the Mediterranean basin. Pintus, 2009: *Preserving natural resources*. Rethinking rural development in the Mediterranean. CIHEAM. Presses de Sciences Po, 27–57. Using the Blue Plan database.

Table 2 Variation in crop yields (maize and tomatoes) according to soil salinity

				Crop yields (kg ha^{-1})	
Soil classes	*Texture 0–30 cm*	*Texture > 30 cm*	*Soil salinity (dS m^{-1})*	*Maize*	*Tomatoes*
s1	Clay-loamy	Clay-loamy	1.95	21741	66085
s2	Loamy	Loamy	5.17	16995	34650

Abbes, K., 2004: Analyse de la relation agriculture environnement: une approche bio-économique. Cas de la salinisation des sols et de la pollution par les nitrates au nord tunisien. Thèse (Dr. d'Université), Faculté des sciences économiques, Université Monpellier I, 313 pp.

is low (Belhouchette 2004). For example, in the CEBALAT irrigated area (northern Tunisia), an increase in the accumulation of salt in the soil is predicted following the increase in water stress (Figure 6).

Nevertheless, the effect of soil salinity is not always linear from 1 year to the next (Belhouchette 2004; Belhouchette et al. 2012). A farmer's capacity to adjust his production activities in terms of the choice of crop and the choice of

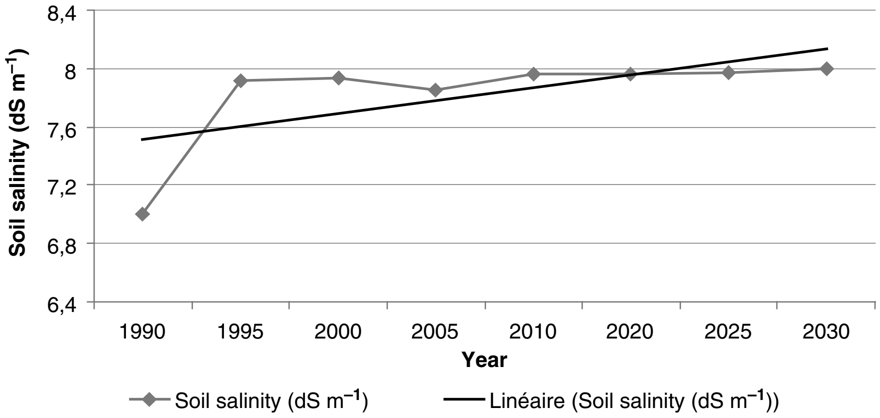

Figure 6 Forecast change in soil salinity until 2030 in the CEBALAT irrigated area (northern Tunisia). Belhouchette, H., 2004: Evaluation de la durabilité de successions culturales à l'échelle d'un périmètre irrigué en Tunisie : utilisation conjointe d'un modèle de culture (Cropsyst), d'un SIG et d'un modèle bio-économique. Thèse (Dr. d'Université en Sciences Agronomiques), ENSA-Montpellier, 155 pp.

irrigation and rotation techniques can cause a reduction in soil salinity.

2.10.4 Farmers' Responses to Climate

Farmers have always responded to socioeconomics, institutions, and climate through improved farm management by adjusting their cropping or production systems. In the coming decades, farmers may have to overcome the double challenge of ensuring the economic and ecological viability of their farms while coping with possible new climate conditions. In addition to the direct impacts on the cropping systems caused by climate uncertainty, they will also be faced with pressure on the availability of, demand for, and accessibility of natural resources, in particular water (Wei et al. 2009).

Nevertheless, the impacts of these climate and socioeconomic changes cause variable impacts according to the biophysical, institutional, and socioeconomic context. More particularly, a high level of variability of cropping system responses to the irregular precipitation and temperatures would almost certainly lead to a disparity in the farmers' responses (Reidsma et al. 2010). The heterogeneity of farmers' responses can be explained by both the structure of the farm (size, technical-economic orientation, etc.) and the related performance indicators (net margin, intensification rate, etc.). The impacts of these factors cannot, however, be generalized as they are very different from one region to another (Reidsma et al. 2009; 2010). In the Mediterranean context, analyzing farmers' responses means taking a complex set of farmers' decisions into account according to both the biophysical (climate, soil, cropping system) and the socioeconomic contexts (prices, quotas, subsidies, etc.) (Belhouchette et al. 2012), which differ between region.

Furthermore, an analysis of the interactions between farm characteristics and the impacts of climate revealed different behavior in the different regions. Farms that appeared to be the least vulnerable to external shocks (economic and agronomic performances) do not necessarily enjoy greater adaptability to climatic conditions (Challinor and Wheeler 2008; Reidsma et al. 2010). Small-scale traditional farms, for example, may enjoy a better capacity for adapting to climate than large-scale intensive farms. Figure 7 illustrates the correlation between farm characteristics and the impacts of temperature on production in different European countries (Reidsma et al. 2010). In France, small-scale farms demonstrate a greater capacity for adapting to climate, whereas this does not hold for either Spain or Greece where the impacts of temperature on production are positively correlated with the economic scale of the farm (Reidsma et al. 2010).

In northern Tunisia, and more particularly among the farms of the lower Medjerda Valley, the farms that succeed in maintaining their income without altering their current operating methods are those characterized by diversified cropping systems based essentially on arable crops, forage crops, and market gardening with a very significant livestock activity. They enjoy greater room for maneuvering through the adjustment of their production activities and the choice of irrigation doses applied as well as more profitable rotations, for example, increasing the area allocated to cereals that are less sensitive to water stress, such as barley and forage crops, at the expense of winter wheat (Figure 8). Farms specializing in tree crops, however, are the most sensitive to climate due to a lack of flexibility at farm level and the high cost of lifting the trees (Chabchoub et al. 2010).

However, short-term objectives aimed at improving farm profitability are often in conflict with long-term objectives concerning the reduction of soil salinity. Figure 9 demonstrates the economic and environmental impacts of farmers' decisions (rational/not rational). The application of rational irrigation doses will certainly cause the farmer's income to fall in the short-term but will be conducive to an increase in the farmer's income in the long-term, while ensuring a relatively low increase in salinity levels. On the other hand, a farmer aiming to maximize income by means of high irrigation doses will eventually find that his soil has a high salt content which will affect crop yields and cause a subsequent fall in the farmer's income (Belhouchette et al. 2012) (Figure 9).

Furthermore, if we consider the assessment of climate at farm level, it is the farm characteristics that explain the variability of its performances. Nevertheless, due to the diversity of

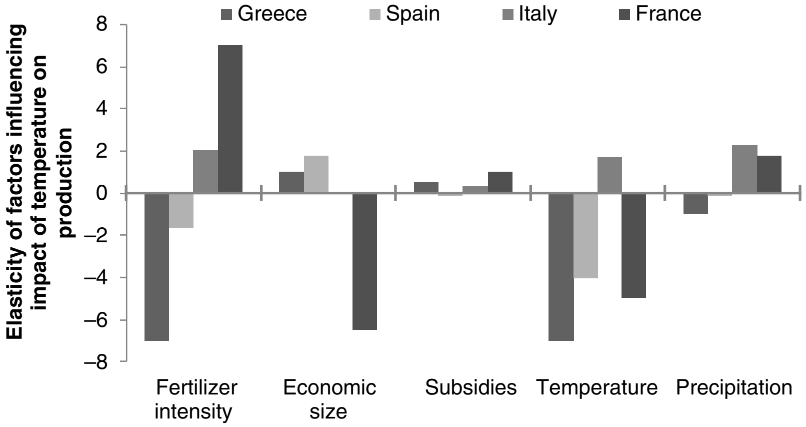

Figure 7 Influence of farm characteristics, climate conditions, and socioeconomic conditions (see Table 1 for a description) on reducing or exacerbating the impacts of higher temperatures on production (temporal variability including interactions, regional level). Reidsma, P., Ewert, F., Alfons, O. L. and Leemans, R., 2010: Adaptation to climate change and climate variability in European agriculture: the importance of farm level responses. *Eur. J. Agron.*, **32,** 91–102, http://dx.doi.org/10.1016/j.eja.2009.06.003.

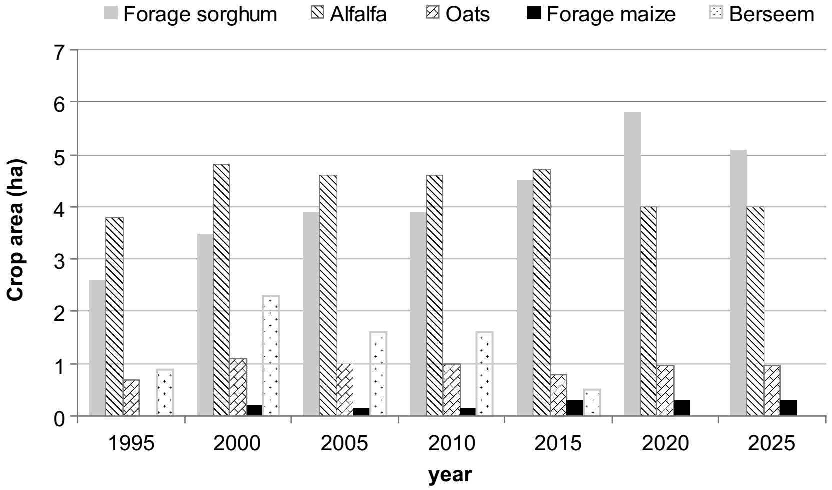

Figure 8 Evolution of the area reserved for each crop in the CEBALAT irrigated area (northern Tunisia). Belhouchette, H., 2004: Evaluation de la durabilité de successions culturales à l'échelle d'un périmètre irrigué en Tunisie : utilisation conjointe d'un modèle de culture (Cropsyst), d'un SIG et d'un modèle bio-économique. Thèse (Dr. d'Université en Sciences Agronomiques), ENSA-Montpellier 155.

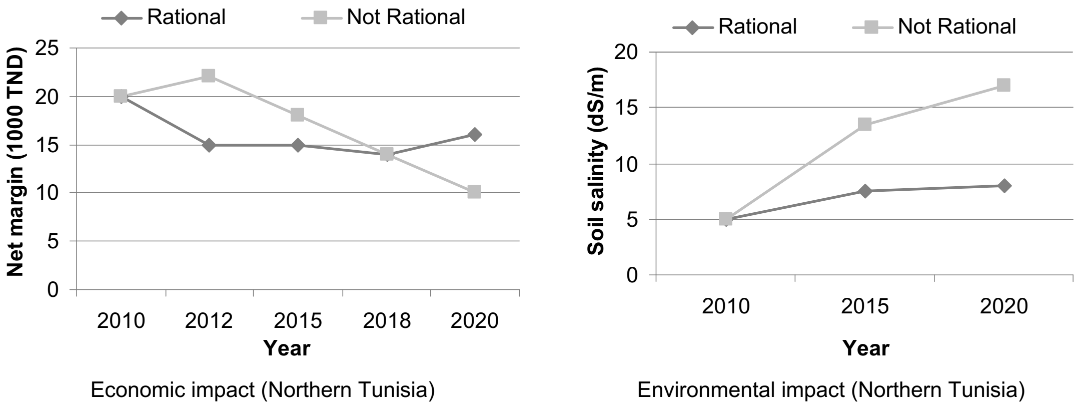

Figure 9 The economic and environmental impact of a farmer's decision concerning irrigation doses (rational and not rational) over 10 years. Belhouchette, H., 2004: Evaluation de la durabilité de successions culturales à l'échelle d'un périmètre irrigué en Tunisie : utilisation conjointe d'un modèle de culture (Cropsyst), d'un SIG et d'un modèle bio-économique. Thèse (Dr. d'Université en Sciences Agronomiques), ENSA-Montpellier, 155 pp.

farms in terms of their structure and performances, the possible adaptations cannot be generalized. It would probably be more profitable, for example, for maize areas in France, as it is a crop that consumes a great deal of water, whereas this strategy would have no major impact on farmers' incomes in other regions (Reidsma et al. 2010). In addition to the variability of maize yields, other factors also play a role in explaining farm performances (agricultural policies, etc.).

2.10.5 The Effects on Cropping Systems

2.10.5.1 The Effects on Crop Water Requirements

In a context of climate, crops are subjected to stress factors that can affect their water requirements, growth, development, and yields (Iglesias and Minguez 1997; Reidsma et al. 2009). The impacts generally depend on the biophysical conditions in each country, the characteristics and particularities of each type of agriculture and the type of crop (Anphoux et al. 2003). Climate factors, in particular precipitation and temperature, have direct effects on the growth of crops. **Figure 10** illustrates the changing water requirements for maize (Midi-Pyrénées class, France), which have risen from 150 mm in 1993 to 300 mm in 2005 under the effect of increasing evaporative demand, with an average of 230 mm (Teyssier 2006). These requirements reached 400 mm in 2003, which was a particularly dry year, especially during the summer. The maximum temperature recorded during the summer in this region was 43 °C (**Figure 10**).

Furthermore, an increased frequency of hot days, in particular during winter and spring, and highly irregular precipitation would probably give rise to an increased water requirement for crops, especially spring and summer crops (e.g., maize), as well as for rain-fed crops such as winter cereals. Studies concerning possible changes in regional climate in the Mediterranean region anticipate increased water demand for spring crops of between 2 and 4% for maize, 6 and 10% for potatoes (PNUE/PAM 2009), and 8 and 10% for winter wheat (Supit et al. 2010).

The water consumption of crops depends on the water retention capacity of the soil and the crops' water requirements (Supit et al. 2010). In the case of the summer crop sugar beet, for example, Supit et al. (2010) demonstrated that the water deficit calculated as the difference between water requirements and water consumption is primarily observed in Mediterranean countries that typically experience hot and dry seasons where the soil is less well-suited to this type of crop. A water deficit of between 14 and 30 mm year^{-1} was recorded in Italy and Greece.

In northern Tunisia, the current irrigation amounts used are insufficient for irrigated summer crops if there is a warming and drying. In the case of maize, for instance, increasing water requirements could reach 58%. It is therefore a question of the irrigation techniques applied by farmers. Concerning rain-fed winter crops, supplemental irrigation is necessary during the sowing period and in spring. **Figure 11** illustrates the water deficit for durum wheat in northern Tunisia between the crop's water requirements and effective rainfall. Water deficit could reach 150 mm in May.

2.10.5.2 The Effects on the Crop Development Stages

Research works confirm that crops positively react to increased concentrations of CO_2 if other aspects of climate do not change (Jablonski et al. 2002), whereas the impacts associated with high temperatures, the intra- and interannual variability of precipitation and possibly the increased frequency of extreme events such as droughts and floods would probably reduce crop yields and increase the risks of a fall in production (Fischer et al. 2007). There are a number of reasons why climate can influence yields both positively and negatively. First, an increase in temperature would shorten the phenological phases. In Spain, for example, the lengths of the growth period of maize could plausibly decrease by 7–21 days (Iglesias and Minguez 1997). This

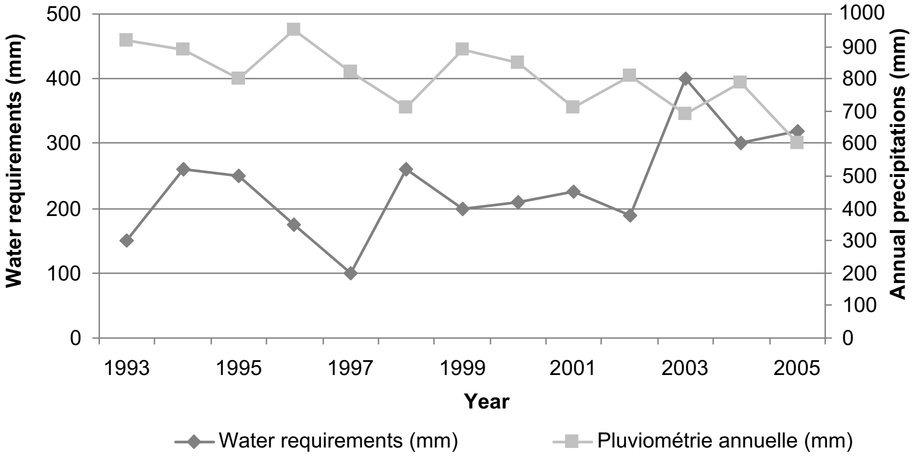

Figure 10 Changing water requirements of Midi Pyrénées-class maize (France) and annual precipitation in millimeters over the period 1993–2005, with an average of 230 mm. Teyssier, F., 2006: Les consommations d'eau pour irrigation en midi-Pyrénées. Surfaces irriguées et volumes d'eau consommés: Rapport avec le climat, la PAC, les ressources sur la période 2001–2005. Direction régionale de l'agriculture et de la forêt de midi Pyrénées. Préfecture de la région Midi-Pyrénées, 42 pp. and ARPE, 2008: Agence regionale pour l'environnement. L'impact du changement climatique en Midi-Pyrénées, Exemple de la chaîne des Pyrénées. UE-ADEME-ARPE, Midi-Pyrénées, 78 pp.

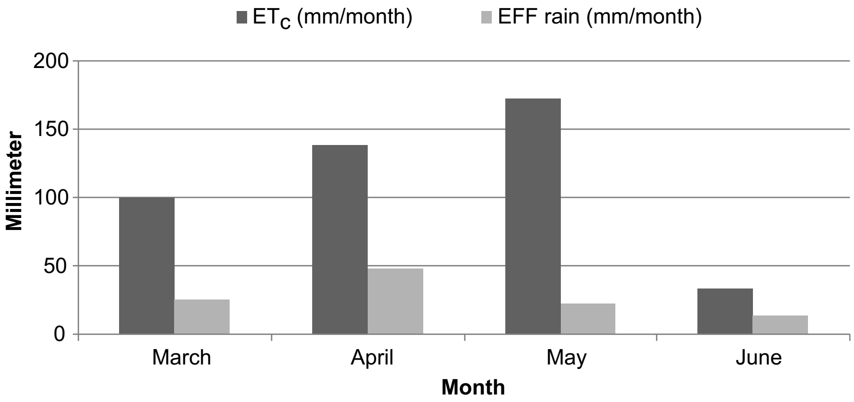

Figure 11 Difference between the crop's water requirements (ET_C) and effective rainfall (EFF rain) for rain-fed durum wheat in spring in the conditions of climate change (2025). Souissi, I. Under development: Résilience et adaptations des systémes de production méditerranéens au changement climatique: Cas de la Basse Vallée de Medjerda. Thése (Dr en sciences économiques), Université Montpellier I, France.

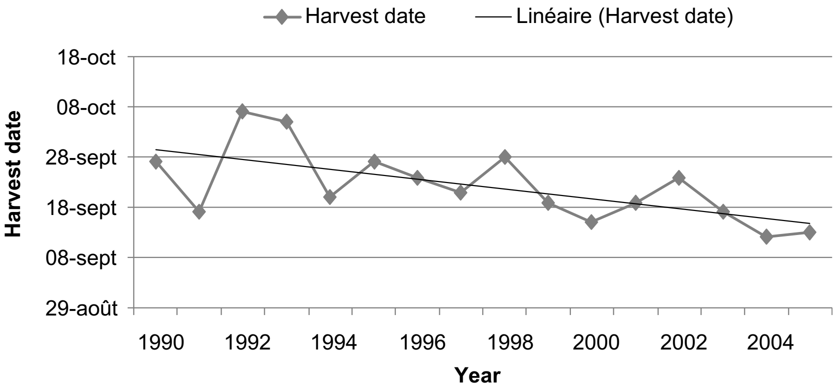

Figure 12 Changing date of the first day of harvest for grapes (BANYULS *cépage*) for the period 1990–2005. ARPE, 2008: Agence regionale pour l'environnement. L'impact du changement climatique en Midi-Pyrénées, Exemple de la chaîne des Pyrénées. UE-ADEME-ARPE, Midi-Pyrénées, 78 pp.

would reduce the time for light and water capture and would reduce water and light use. A simultaneous decrease in precipitation would reduce water availability. Accelerated crop development and a short grain-filling period would reduce grain yield, for example with a plausible fall of about 24% for wheat in Spain (Iglesias and Minguez 1997), whereas the additional carbon available will create an initial yield increase because of increased light and water use efficiencies. For instance, an increase of CO_2 ($+600\ \mu mol^{-1}$) leads to a 30 and 8% increase in wheat and maize yield, respectively, in Spain (Iglesias and Minguez 1997).

Several studies have analyzed the changes observed at the crop development phase level. In the Mediterranean basin, where water availability is already limited, in particular in the south and east, an increased summer temperature would have the effect of shortening the growth period of the crops, thereby offering less time to accumulate biomass (Rosensweig and Tubiello 1997). In the case of annual crops in Morocco, for example, the time between sowing and harvesting could be reduced causing a shortening of the growth period of 70 days (Benaouda and Balaghi 2009).

Perennial crops are also affected by these phenomena. Following a temperature increase, the phenological stages of fruit trees would be brought forward causing a deterioration of the intensity of flowering resulting from the reduction in cold episodes (Benaouda and Balaghi 2009). Figure 12 illustrates the changing harvest date for the BANYULS *cépage* (*cépage*: The BANYULS *cépage* is a variety of vine very common in the northern Mediterranean region) for the period 1990–07 in the Midi-Pyrénées region (France). Over 17 years, the harvest date has moved forward by about 15 days on average. These changes to the growth cycle of the crops will probably have a direct effect on crop yield.

The response of agricultural systems to climate also depends a great deal on farming practices (the amounts and frequency of irrigation and fertilizers) (Tubiello et al. 2000). In conditions where water is limited, for example, the effect of high concentrations of CO_2 is positive in relation to conditions where the crop is well watered (Chaudhury et al. 1990; Kimball et al. 1995). When the nitrogen inputs are high, the crop responds more positively to CO_2 than crops with less fertilizer (Sionit et al. 1981; Mitchell et al. 1993).

For the Tunisian case study, Table 3 summarizes the average and standard deviation of the duration of each phenological stage and the duration of the overall growing season for two strategic cropping systems for the Mediterranean region such as Tunisia: wheat and maize.

Table 3 Summary of the average and standard deviation of the duration of wheat (sowing date 18 December) and maize (sowing date 2 April) phenological stages and the length of the growing season calculated from 1995 to 2025

			Flowering	*Grain filling*		
		Emergence	*Days after sowing*		*Maturity*	*Length (day)*
Wheat	Mean	25	96	120	148	164
	SD	2.6	2.5	2.6	3.2	3.2
Maize	Mean	14	53	61	115	116
	SD	1.7	3	3.4	8.5	8.5

Temani, N., 2010: Assessing wheat and maize cropping systems responses to the uncertainty of climate change: Application to an irrigated area in Northern Tunisia. Mémoire de fin d'études, SUPAGRO et IAMM, 43 pp.

From 1995 to one scenario for 2025 a slight variation in the duration is observed during emergence, flowering maturity, and grain filling for wheat and maize. In both cases, the highest variability occurs during the maturity phase with a standard deviation of 3.2 days for the two cropping systems.

Table 3 shows that from 1995 to a plausible scenario for 2025, maize emergence occurs 14 days (±1.7 day) after sowing. Anthesis and grain filling require 53 days (±3 days) and 61 days (±3.4 days) respectively, while maturity varies by 5.5 days. The phenological stages would occur earlier and crop seasons would be shortened (Iglesias and Minguez 1997). In this study, we calculate a change of 8.5 days in the length of the growing season, simulated under higher atmospheric CO_2 concentration, increased temperature, and altered precipitation.

2.10.5.3 The Effects on Crop Yields

The impacts of climate on crop yields are generally estimated by means of biophysical models using climate data produced by regional circulation models or general circulation models, or by experimental data. These yield a subset of plausible regional climate conditions in the coming decades. A certain number of crop simulation models, such as CERES-Maize (Crop Environment Resource Synthesis), CERES-Wheat, SWAP (Soil–Water–Atmosphere–Plant), CropSyst (Stöckle et al. 2003), and InFoCrop (Aggarwal et al. 2006), have also been widely used to assess the possible impacts of climate on agricultural production, and more particularly to analyze the sensitivity of crop yields to the different climate scenarios.

Using a subset of plausible climate scenarios in the Mediterranean basin (Meehl et al. 2007), crop yields would be subject to major change. These changes are not homogeneous and depend on the phenology of the crops, the type of crop (e.g., C3 or C4), and the environmental conditions (the availability of water and nutritive elements) (Antipolis 2008). Agriculture in the southern countries would probably be more affected by these effects. Several works have focused on studying the variation in crop yields for the different IPCC scenarios. The results obtained for these different studies predict that rain-fed crops would be directly affected by climate change. In Italy, for instance, an increase in air temperatures would accelerate the phenology of the plants, thereby reducing the accumulation of dry matter and reducing wheat yields by between 30 and 50% (Tubiello et al. 2000). In Australia, the reduction would be 15% (Ludwing and Asseng 2010). Applying the CROPWAT model (Food and Agricultural Organization) to winter cereals in Morocco shows a reduction in yield of 10% in a normal year and of 50% in a dry year by 2020 using the IPCC subset of plausible scenarios as well as a 30% fall in national production. In Algeria, average reductions in crop yields of between 6 and 14% are simulated.

The IPCC scenarios also show an effect on vegetables, with a productivity variation of between –30 and +5% simulated for 2050. In Algeria, vegetable yields are predicted by the IPCC models to decrease by between 10 and 30%. This fall would reach 40% in Morocco by 2030 according to these models (PNUE/PAM 2009).

An occurrence of extreme events during the crop development cycle (rain during sowing or drought during flowering) or more intense precipitation and longer droughts would also reduce summer crop yields. In addition to the effects of climate, other factors can cause crop yields to fall, such as the appearance of new pests and parasites (PNUE/PAM 2009). In Italy, for example, the yield of sorghum, which is a summer forage crop, could fall by between 10 and 30% (Tubiello et al. 2000).

For the Tunisian case, a study is conducted by Temani (2010) in the CEBALAT catchment area (northern Tunisia) to determine the behavior of maize and wheat in a context of climate. To this end, 30 years of weather data were analyzed in order to define the precipitation scenarios most closely matching that of the Cebalat region (an average precipitation of 470 mm). Inter- and intraannual variability led to high standard deviations. Three rainfall patterns are chosen based on rainfall probability: dry, average, and wet years (with probabilities of 30, 50, and 20%, respectively).

Simulated grain yield in the three precipitation scenarios shows a decrease of 25% between average and dry years, while the same rate of decrease is maintained for the difference in the Above Ground Biomass (AGB) in these 2 years (Figure 13). A sensitivity analysis was conducted to test the effect of the variety's sensitivity to water stress on grain yield. A tolerant variety produces 300 kg ha^{-1} of grain more than a sensitive variety.

As mentioned in Figure 13, the dry year has the lowest grain yield; therefore, the water, temperature (Figure 14), and salinity stress occurring during the wheat growing season of the dry year was monitored. No water stress appears throughout the entire growing period. Salt accumulated in the top meter does not exceed 1 dS m^{-1} while heat stress occurs from the beginning of the vegetative period to the grain-filling stage (Figure 14). It has already been reported that grain yield is

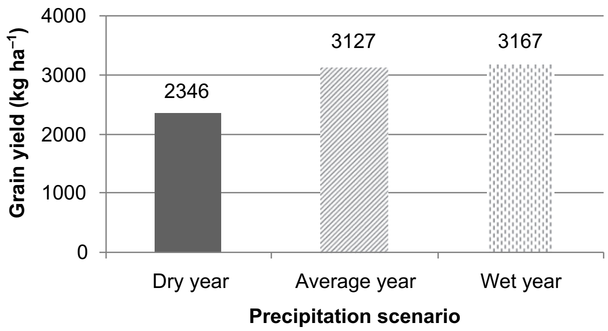

Figure 13 Simulated wheat grain yield obtained in the three precipitation scenarios. Temani, N., 2010: Assessing wheat and maize cropping systems responses to the uncertainty of climate change: Application to an irrigated area in Northern Tunisia. Mémoire de fin d'études, SUPAGRO et IAMM, 43 pp.

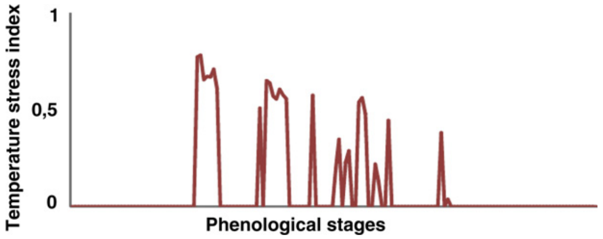

Figure 14 The evolution of the temperature stress index during the dry year wheat growing season. Temani, N., 2010: Assessing wheat and maize cropping systems responses to the uncertainty of climate change: Application to an irrigated area in Northern Tunisia. Mémoire de fin d'études, SUPAGRO et IAMM, 43 pp.

negatively correlated to maximum temperature (Wang et al. 2006). Gate (1995) highlighted that some extreme temperatures occurring in specific phases of development may lead to an additional fall in grain yield. In Figure 15, therefore, the maximum temperature distribution is examined during the accumulation of wheat AGB in the dry year to detect if such a phenomenon occurs.

In active growth, the maximum temperature exceeded 22 °C for 5 days. Gate's experimental data (1995) has shown that the optimum temperature during this phase is 12 °C. Beyond this optimum, the number of fertile flowers gradually decreases as the temperature rises. This confirms Wang et al.'s (2006) observation that a temperature exceeding 23 °C occurring during the reproductive period significantly reduces grain yield.

During grain filling, the optimum temperature to achieve maximum kernel weight is 15–18 °C. Warmer temperatures up to 30 °C mainly affect assimilate availability, translocation of photosynthates to the grain, and starch synthesis and deposition in the developing grain. This leads to a lower grain yield due to lower thousand-grain weight (Modhej et al. 2008). For the Tunisian dry year simulation, temperature during the grain-filling phase in 2019 ranges from 18 to 31 °C, generating heat stress expressed by a value of 0.5 on the temperature stress index. Figure 15 shows severe heat stress during the early growth stage. In addition, the wheat cutoff temperature is 25 °C. In the dry year, the temperature exceeds 25 °C on 19 days, reaching a maximum of 33 °C where growth stoppage is possible.

Figure 16 shows that maize grain yields from 1995 to 2025 are very low compared to other regions. This large difference between yields is due to the fact that maize is generally sown in spring in the northern part of the Mediterranean, whereas in the Tunisia case it is a summer crop sown in July giving a simulated grain yield of 4 tons ha^{-1}.

The highest yield is obtained in 2010 (3 tons ha^{-1}), while the lowest was that of 2003 with a yield 66.2% lower. In order to explain the main reasons for such a drop in yield, the curves of water stress, heat stress, and soil salinity observed during the maize growing season are presented in Figure 17, which shows that heat stress occurred from flowering to maturity. The temperature stress index reached a maximum of 0.9 in the grain-filling phase, which is very sensitive to temperature. In general, the grain-filling rate decreases as mean temperature drops (Wilkens and Singh 2001). Furthermore, severe water

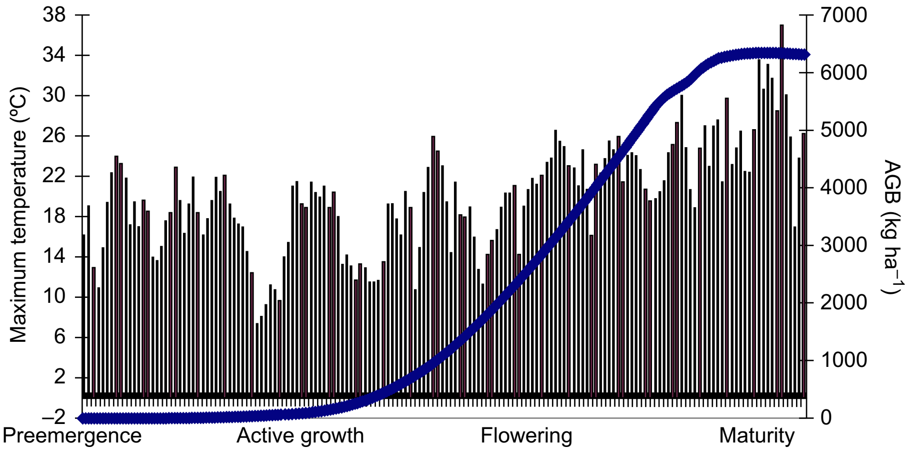

Figure 15 Simulated maximum temperature during AGB accumulation during the dry year. Temani, N., 2010: Assessing wheat and maize cropping systems responses to the uncertainty of climate change: Application to an irrigated area in Northern Tunisia. Mémoire de fin d'études, SUPAGRO et IAMM, 43 pp.

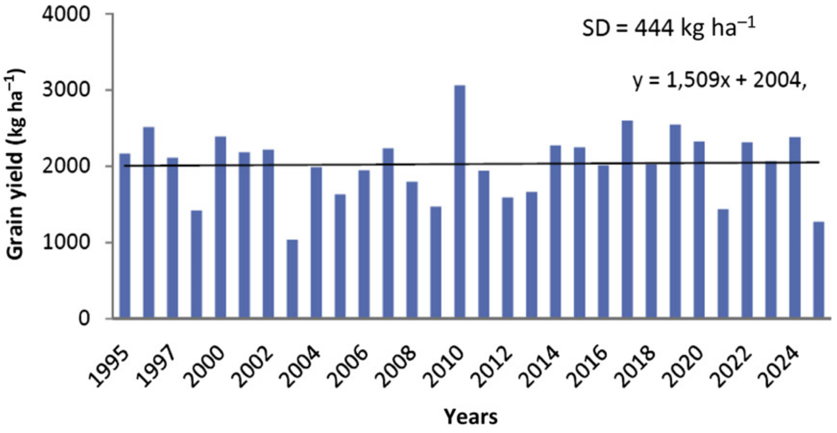

Figure 16 Simulated annual maize grain yield for the period 1995–2025. Temani, N., 2010: Assessing wheat and maize cropping systems responses to the uncertainty of climate change: Application to an irrigated area in Northern Tunisia. Mémoire de fin d'études, SUPAGRO et IAMM, 43 pp.

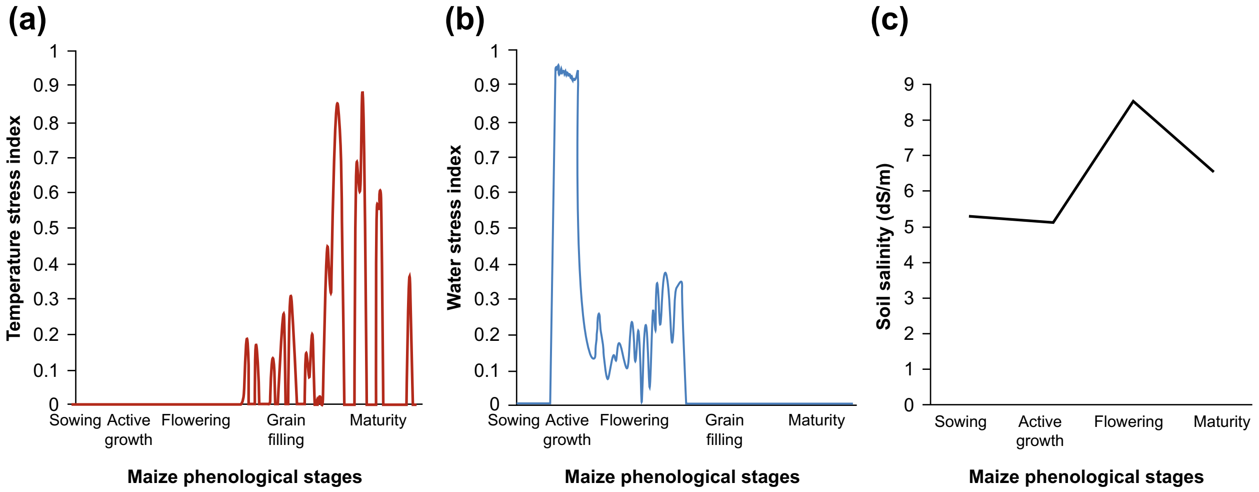

Figure 17 Evolution of types of stress during maize growth in 2003. Evolution of (a) the temperature stress index, (b) the water stress index, and (c) the average soil salinity in the top meter during the maize growing season. Temani, N., 2010: Assessing wheat and maize cropping systems responses to the uncertainty of climate change: Application to an irrigated area in Northern Tunisia. Mémoire de fin d'études, SUPAGRO et IAMM, 43 pp.

stress (water stress index = 0.9) was observed during active growth, which is a very critical and sensitive period for water storage (Gate 1995). Water stress continues to a lesser extent until grain filling, increasing the risk of compromising the grain yield. Despite irrigation, maize still suffers from water stress. This is probably due to the high soil salinity that reached 8 dS m^{-1} during the flowering stage. Thus, salinity, water stress, and heat stress led to the low yield obtained in 2003. However, water stress seems to be the main reason behind this result. In 2010, despite high salinity and temperature stress, yields were 66% higher than in 2003 (Figure 18).

2.10.6 Conclusion

Mediterranean agriculture is a sector that is particularly sensitive and vulnerable to climate (Ewert et al. 2005). Increased variability of precipitation and temperature would have several impacts (both positive and negative) on natural resources, the crop development cycle, crops yields, and farmers' incomes while demonstrating regional disparities. The impacts of climate on the agricultural production systems are the result of complex and strongly contrasting mechanisms, which are closely linked to the institutional, socioeconomic, and geographic situations of each country. The most unfavorable regions are not necessarily the most vulnerable to climate variability (Challinor et al. 2009; Reidsma et al. 2010). For instance, in the Mediterranean basin, the diversity of farms in terms of size and intensification rates reduces the regional vulnerability of wheat yields (Reidsma and Ewert 2008). Furthermore, the diversification of farms could be a strategy for adapting to the variability of temperatures and precipitation. In this context, others' adaptations can be recommended to reduce the negative reactions of crops to climate (e.g., adopting specific farming conduct methods: modification of sowing dates, etc.). However, "these methods could require up to 40%

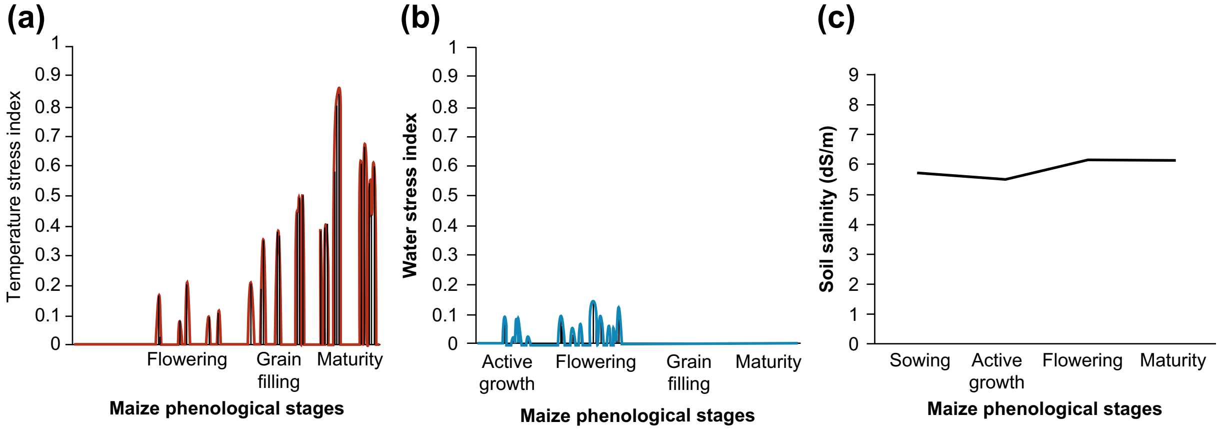

Figure 18 Evolution of types of stress during maize growth in 2010. Evolution of (a) the temperature stress index, (b) the water stress index, and (c) the average soil salinity in the top meter during the maize growing season. Temani, N., 2010: Assessing wheat and maize cropping systems responses to the uncertainty of climate change: Application to an irrigated area in Northern Tunisia. Mémoire de fin d'études, SUPAGRO et IAMM, 43 pp.

more water for irrigation, a volume of water which could prove essential in certain regions in the future" (PNUE/PAM 2009). Adaptation strategies cannot therefore be generalized and depend on the biophysical, socioeconomic, and political characteristics of each region. An increased number of specific studies must be conducted for each region to assess the resilience of the production systems and the possible adaptation strategies.

Determining the responses of the cropping and farming systems to climate as well as the possible adaptation capacities means taking account of the different elements that can affect farmers' decisions with regard to the environment of the system (socioeconomic, political and institutional, biophysical) and the characteristics of the biophysical systems (soil types, technical choices, etc.).

Several prospective studies indicate that, in addition to water scarcity and quality, several drivers will make the Mediterranean agricultural systems more vulnerable:

- The Mediterranean Region (MR) population is increasing (expected to increase from 446 million in 2000 to 579 million in 2025) and the region is characterized by important movements of population due to economic and social reasons or even to local conflicts. The economy tends to be more global and the ways of life more uniform, particularly in terms of food and leisure, which is strengthening the relations between urban and rural areas (Pintus 2009).
- Climate already modifies the physical and biological environment of agriculture in the MR: an increase in average temperature and decrease in precipitations, invasions by new pests and weeds, higher frequency of extreme events (drought, flooding, heat, storms,…). It tends to reduce the availability of water, increase risks (losses in yield and livestock, erosion,…), and threatens the sustainability of most farming systems.
- Public policies aim at increasing agricultural production, reducing poverty, and limiting migration to cities or abroad. They tend to concentrate agricultural production in regions where the prevailing farming systems tend to specialize in few crops and animal products of high added value, thereby stimulating the intensive use of water, chemicals, and soil resources. In the margins, small farms survive with a lower availability of resources and a more intensive use of labor, often by combining incomes from different sources (agricultural and nonagricultural activities, emigration).
- Local organizations are rarely neutral with regard to local development process and particularly agricultural production. They may facilitate local actors' representations in the decision-making process; they may also reflect conflicts of interests between different groups of actors. But they may also bring knowledge and innovations that could be meaningful at a higher level. In all cases, they take part in the regional development process. This is still rarely studied in the southern part of the Mediterranean basin, where local development is being implemented since the year 2000.

In this context, the challenge is to develop methods and tools allowing one to assess the vulnerability of Agricultural Systems of the MR, to these policies where economic and climatic impacts simultaneously occur. This question should be addressed with regard to the diversity of the contexts (institutional, socioeconomic, and environmental) and of the farming systems.

Scaling between different organization levels and integrating visions and options from a range of disciplines (e.g., agronomy, ecology, economic, and sociology) (Van Ittersum et al. 2008) are then vital for a sufficiently broad perspective on vulnerability and adaptive strategies of agricultural systems. One of the obstacles to the operational integration of different disciplines is the variety of formalisms, which is, for example, reflected in the models and the 'preferred' scales of analysis in the research projects of each discipline. As a result, different research groups of the MR have developed projects with similar aims but with incompatible software tools and a lack of analysis of the interactions between social, environmental, and economic systems. Models, data, and methods (scenario, indicators, typologies, scaling methods, etc.) are generally less generic than they are aimed for, and the conditions of their reusability in a new MR are poorly defined.

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Support site for Blue Plan. http://www.planbleu.org/.
Support site for Fondazione Eni Enrico Mattei. http://www.feem.it/.

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2.11 Freshwater Wetlands: Balancing Food and Water Security with Resilience of Ecological and Social Systems

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2.11.1 Introduction

Wetlands are essential ecological components of landscapes that provide numerous socioeconomic and ecological services. The global distribution of wetlands is shown in Figure 1. Increased food production, urbanization, and human appropriation of freshwater have contributed to the loss of wetlands all over the world and threaten the ecological integrity of the remaining wetlands. Major land use and land cover (LULC) changes over the past century of rapid economic development and population growth have contributed to large-scale losses of critical wetlands, with the loss estimated at approximately 50% globally and 54% in the United States (OECD 1996); by 1985, conversion of wetlands to croplands accounted for a global loss of 26% of wetlands (OECD 1996).

Time series of changes in potentially saturated areas, some of which support wetlands, over a 350-year period (1650–1992) were mapped by Steyaert and Knox (2008), illustrating the shifting spatial patterns in the eastern half of the United States. Engineered landscape drainage beginning in 1920 contributed to the large-scale loss of wetlands (see Figure 2). Pressures from the continued need to double food production to meet increasing global demands with population growth, projected to plateau at approximately 10 billion (United Nations 2010), as well as rapid urbanization and growing affluence, are currently converging to threaten the remaining wetlands. For example, in eastern United States, land clearing began in 1600 and steadily escalated until 1920 with drastic LULC changes (e.g., deforestation, land drainage, intensive land use) and once again morphed with some reforestation, urbanization, and intensive agriculture (Steyaert and Knox 2008); these patterns of change reflect the shifting patterns of population and economic growth and also the socioeconomic priorities.

In the past, important ecological services have been traded off to gain socioeconomic services. The consequences of these choices are manifested in impaired water quality, loss of habitats and biodiversity, and other indicators. Draining wetlands has contributed to control of diseases such as malaria, but other adverse public health impacts from wetland loss are more difficult to document (The National Academies 2011). Like other environmental issues, human societies may not be directly impacted, at least in the short term, from loss of aquatic habitats or biodiversity. Yet, long-term cumulative negative impacts of wetland losses and impairment have not been compelling enough to significantly change the trade-offs that societies have made to date. The exceptions are of course the large wetlands, such as the Everglades in Florida.

http://dx.doi.org/10.1016/B978-0-12-384703-4.00238-0

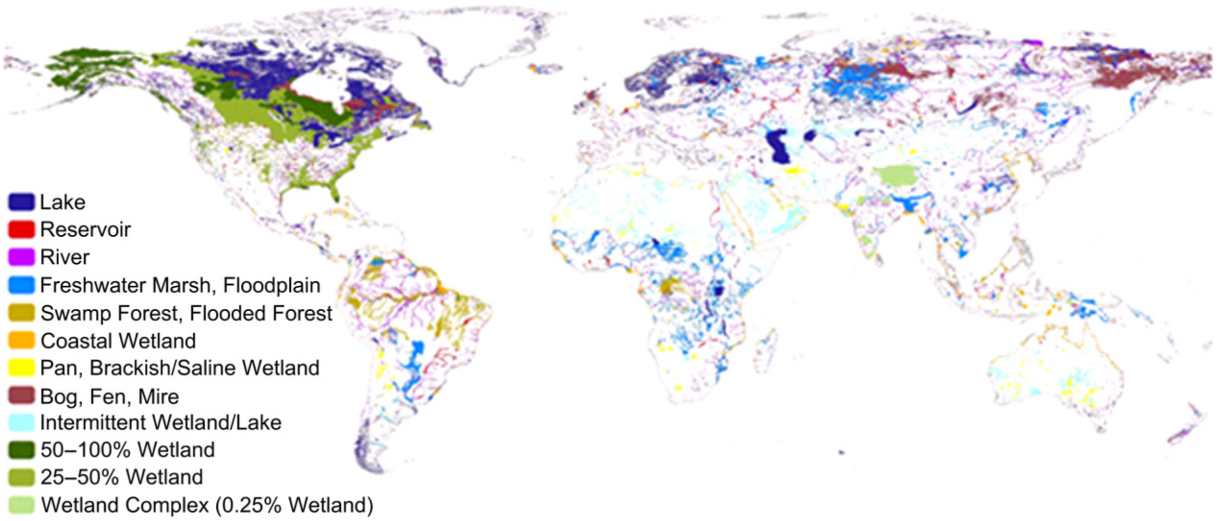
Lake
Reservoir
River
Freshwater Marsh, Floodplain
Swamp Forest, Flooded Forest
Coastal Wetland
Pan, Brackish/Saline Wetland
Bog, Fen, Mire
Intermittent Wetland/Lake
50–100% Wetland
25–50% Wetland
Wetland Complex (0.25% Wetland)

Figure 1 Global spatial distribution of wetlands. Source: Lehner, B. and P. Döll, 2004: Development and validation of a global database of lakes, reservoirs and wetlands. *J. Hydrol.*, **296**, 1–22.

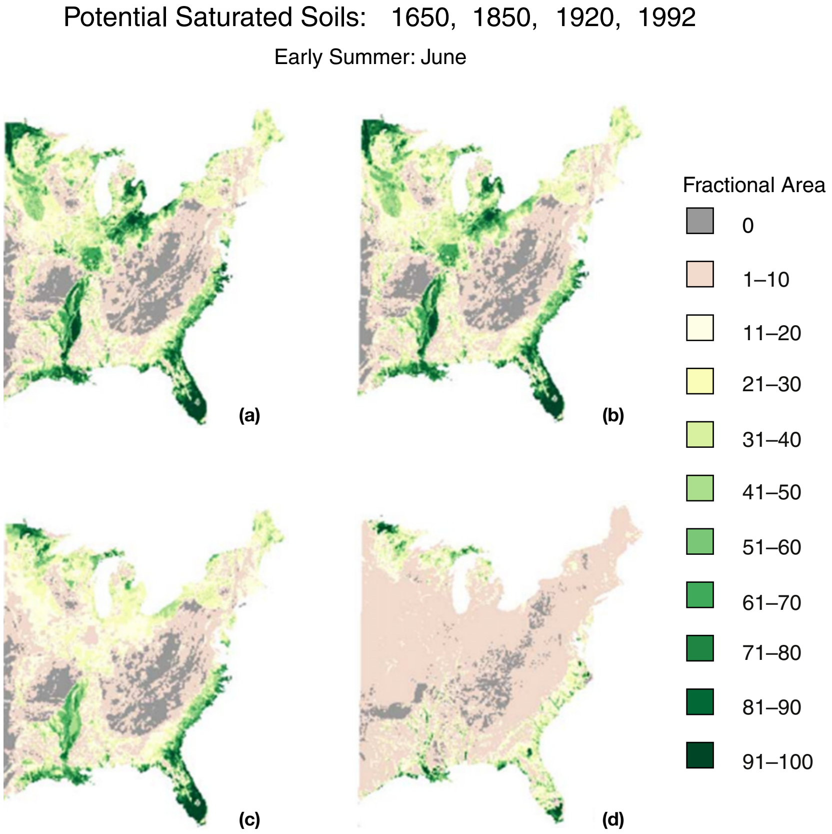
Potential Saturated Soils: 1650, 1850, 1920, 1992
Early Summer: June
Fractional Area
0
1–10
11–20
21–30
31–40
41–50
51–60
61–70
71–80
81–90
91–100
(a)
(b)
(c)
(d)

Figure 2 Estimated changes in land areas, expressed as a fraction of total area, with potentially saturated soils in the eastern United States. (a) 1650, (b) 1850, (c) 1920, and (d) 1992. Source: Steyaert, L. T. and R. G. Knox, 2008: Reconstructed historical land cover and biophysical parameters for studies of land-atmosphere interactions within the eastern United States. *J. Geophys. Res.*, **113**, D02101.

During the past century, increased understanding and recognition of the importance of wetlands has resulted in significant research efforts and programs to restore wetlands, regulations to prevent loss of remaining wetlands, and construction of new wetlands. Natural wetlands have evolved over geological time scales, and the landscapes dominated by wetlands possess diverse structures as an outcome of self-organization and adaptations and multiple interconnected functions that promote landscape resilience. However, direct and indirect anthropogenic impacts (e.g., LULC changes, climate, and freshwater appropriations) have eroded the resilience of natural wetlands, diminishing their quantity and quality.

Although constructed wetlands intended to replace the losses of natural wetlands are important ecological habitats for a large number of species, the range of services that constructed wetlands provide often encompasses a much narrower spectrum than their natural counterparts. Constructed wetlands have been installed as best management practices in agricultural and urban landscapes to mitigate the export of nutrients and other contaminants to receiving water bodies. However, the efficiency of this function may degrade over time (e.g., due to saturation of nutrient removal capacity) and contribute to even further loss of the original functionality of the landscape. For these reasons, we project a continual decline in the total services provided by wetlands at regional and global scales.

Any type of evaluation of the importance of wetlands must first begin with the recognition that the linkage between human societies and ecosystems varies among rural and urban populations. Urban populations are spatially disconnected from distant wetlands, other than a few constructed wetlands within the metropolitan areas, which serve a limited range of functions. Buffered by technologies, urban communities may not be aware of or may not pay for the consequences of wetland losses or their functional impairment. As such, urbanites may have a cognitive disengagement from the state of wetlands, and they may only be aware of certain functions that immediately benefit them, such as flood mitigation. Therefore, urban social resilience has little dependence on wetlands, except during extreme hydrologic events (e.g., flooding of New Orleans by Hurricane Katrina in 2005).

Rural populations in countries with developing economies are keenly aware of wetland services because they provide key elements of food and water security and cultural values. Loss of wetlands would have direct and immediate impact on such communities, and their socioeconomic resilience is directly and strongly linked to wetland functions and landscape resilience. Rural communities in western societies, and countries with advanced economies, have contributed to the large-scale landscape transformations and have directly benefited from conversion of wetlands to croplands and urban areas. Impairments of water quality and loss of ecological services are manifested at local, regional, and national scales, and yet these communities are not necessarily aware of the direct or indirect impacts of such losses. This is, in part, due to difficulties in economic valuation of ecological services provided by ecosystems, including wetlands (The National Academies 2011).

Here, we consider freshwater wetlands, distributed across landscapes, with physical attributes that vary in time and space at multiple scales depending on hydroclimatic forcing (e.g., rainfall patterns), landscape topography, vegetative cover, and hydrological/ecological connectivity as well as anthropogenic impacts. These variables also determine spatial distribution and organization of wetlands in the landscape and their ecological *connectivity*, expressed as the topological attributes of complex dynamic networks. Furthermore, hydrologic fluctuations, duration of the hydroperiod (i.e., the amount of time that the wetland has standing water over the course of a year), temporal variations in hydrologic connectivity (surface and subsurface), and vegetation dynamics define the habitat quality and play key roles in biogeochemical and ecological processes.

We first provide a brief overview of important wetland characteristics and explore the loss of wetlands over time from a network perspective (see Section 2.11.2). Multiple functions of wetlands and the services they provide are summarized in Section 2.11.3. In Section 2.11.4, we review policies and regulations designed to prevent further losses of wetlands. In Section 2.11.5, we offer guidelines for restoration of natural wetlands and management of constructed wetlands. We base our review on the following key questions:

1. Given the importance of wetlands to the long-term sustainability of food production, ecological services, and flood protection, what are the optimal strategies for restoration of wetlands with these conflicting socioeconomic and ecological goals?
2. What are the current criteria for restoration of wetlands? What criteria should exist to successfully regain lost ecosystem services, either by construction of new wetlands or by restoration of impaired wetlands?

2.11.2 Wetlands as Complex Systems

An all-encompassing definition for something as complex and significant as a wetland is difficult to provide. Scientists are apt to focus on research criteria and classification schemes, while politicians may prefer regulatory standards defined using simpler criteria (Mitsch and Gosselink 2007). Many definitions characterize wetlands based on their hydrology, soils, and vegetation. Wetlands may be grouped into three types: (1) *permanent*, with limited variation in water levels; (2) *seasonal*, with water level fluctuations that are closely linked to seasonal differences in hydroclimatic drivers; and (3) *ephemeral*, with the wetland becoming dry for extended periods during a year. These types of wetlands are intrinsically linked to the hydroclimatic regime in which they are located as well as the size of the wetland and its position within the landscape. A wetland in a humid climate is likely to have lower variability in its hydroperiod, as the timing and amounts of rainfall are less variable in humid and tropical climates as compared to semiarid and arid climates. Therefore, permanent wetlands are likely to be larger wetlands located in humid and tropical climates and positioned in landscapes such that they have large contributing areas. Under these conditions, the amount of surface runoff generated from the contributing drainage area plus the net groundwater flows can sustain the water level in permanent wetlands. Such wetlands are less sensitive to variations in hydroclimatic drivers. Seasonal and ephemeral wetlands are likely to be midsized or smaller wetlands in semiarid and arid climates and are water limited in that the total net radiation energy exceeds the amount of water available for evapotranspiration. In contrast, humid areas are energy limited because the net radiation energy available is less than the volume of water received as precipitation. Thus, smaller wetlands are sustained by runoff from the contributing area, reducing the amount of temporal variability in a wetland's water level. As the types of vegetation and aquatic species that a wetland can support are directly related to the wetland's hydroperiod, classifying a wetland into these three categories is an important first step toward understanding the potential ecological functions that a wetland can sustain.

Several studies have focused on single wetland features, providing an in-depth understanding of the hydrological, biogeochemical, and ecological processes and their interdependencies. For the current discussion, we view wetlands as interconnected nodes in a dynamic complex system, characterized by a web of interdependent internal processes with coupled hydrological, biogeochemical, and ecological consequences. Wetlands are subject to stochastic natural and anthropogenic forcing and have multiple functions that vary over time. In this sense, each wetland might be considered as a complex system in its own right, but we instead examine wetlands as nodes in a network that are distributed across the landscape. Thus, the collective, larger scale functionality and dynamic connectivity of the entire landscape are of interest, especially in terms of the ability to maintain functions under fluctuating conditions, i.e., landscape resilience.

Wetlands in a landscape usually occupy the areas with the lowest elevations. Water levels within wetlands are sustained by runoff from landscape units at higher elevations, from the rise and fall of the local water table or from the stage and discharge dynamics and geomorphology of stream networks. Thus, wetlands (1) serve as hydrologic buffers to mitigate floods; (2) modulate solute loads exported from the landscape through uptake, sequestration, transformations, and retardation; and (3) provide dynamic ecological habitat networks and refuges.

2.11.2.1 Size Distribution

Data compilations (Lehner and Döll 2004; Liu and Schwartz 2011; Zhang et al. 2009) have shown that the wetland area distribution across landscapes tends to follow asymmetrical probability density functions (pdfs). The pdfs of other landscape features, such as lakes, have been shown to follow power law distributions (Downing et al. 2006). An analysis of the wetland sizes in the United States (**Figure 3**) shows that wetland area distribution follows a power law [$p(A) = \alpha A^{-\beta}$], where $p(A)$ is the probability of the occurrence of a wetland of a specific area, A, with α and β being empirical constants.

We note that the area cumulative distribution function (cdf) for different states coalesce surprisingly into only two groups for wetlands greater than 100 m^2. The vast majority of states (>90%) have the same value of β ($=1.1 \pm 0.3$), indicating that the processes controlling wetland formation in these states act in such a way that generates scale-invariant patterns, since a single value of β can be fitted across the entire cdf (**Figure 3**). However, four states (Rhode Island, Delaware, Connecticut, and Hawaii) cannot be characterized by this same value of β, likely due to spatial constraints of small geographic areas of these states. Geographic and landscape constraints limit the largest size of wetlands, while the formal definition of an area delineated as a wetland has a certain minimum size. Thus, the power law pdf may be cutoff, or truncated, on both ends (i.e., smaller and larger wetlands), and other pdf models may be more appropriate (e.g., log-normal, gamma, exponential, etc.). This type of analysis facilitates the multiscale assessment of hydrological, biogeochemical, and ecological processes. In Section 2.11.2.3, we will examine how the area pdfs shift in time with stochastic hydroclimatic forcing.

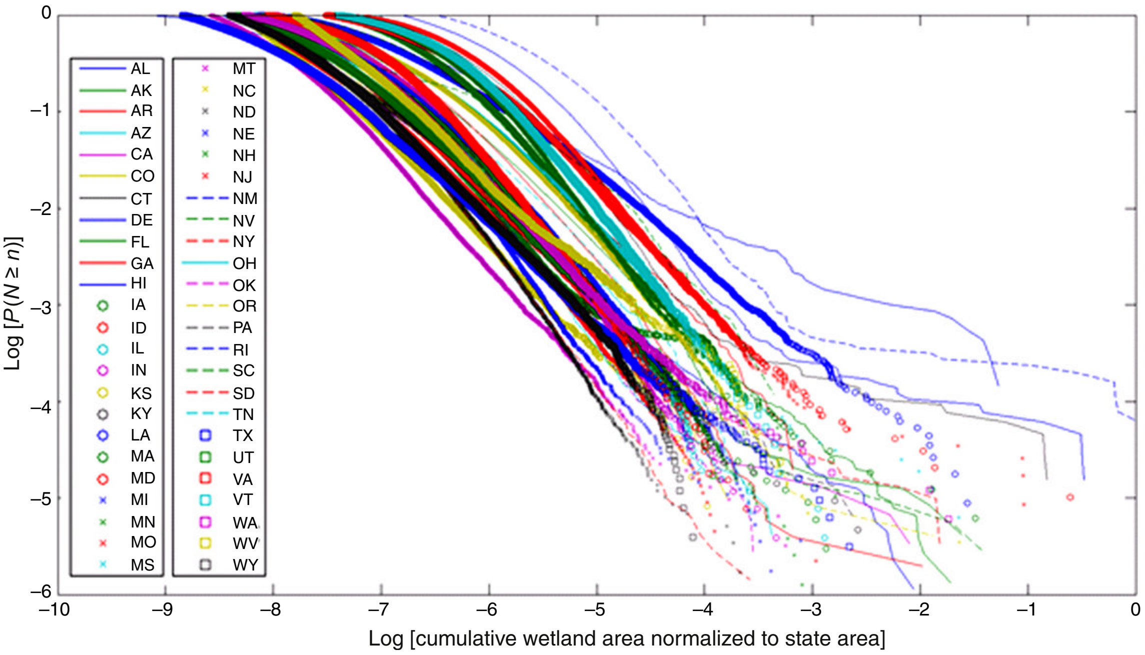

Figure 3 Inverse cumulative distributions of wetland sizes in the United States by state, normalized to the state's area. Data include all wetlands greater than 100 m^2. Data source: USFWS cited 2012: Download Seamless Wetlands Data by State. [Available online at: http://www.fws.gov/wetlands/data/State-Downloads.html.]

2.11.2.2 Wetland Connectivity

Hydrological connectivity of spatially distributed wetlands can occur through (surface) stream networks, through (subsurface) groundwater, or both. Nodes represent individual wetlands, and the hydrological and biogeochemical links are the surface and subsurface water and solute flows between any two nodes. However, we must also consider the ecological links between nodes, which may or may not depend on the hydrologic links, i.e., the dispersal strategies and dispersal ranges of aquatic organisms determine the type of ecological connectivity. Networks can also have directional dependence (e.g., water, solute, and energy flows), in which case they are considered as being *directed* networks. In other cases (e.g., ecological flows), the network flows can be multidirectional. Directed and undirected networks exhibit different abilities to maintain network functions with the loss of nodes and links; thus, landscapes with directed or undirected networks exhibit different degrees of resilience to external perturbations.

Networks are characterized by the distribution of the number of links each node has; this is known as the *node–degree* distribution. The node–degree distribution follows a power law pdf for fractal networks, characterized by scale-invariant network topology. Fractal networks possess 'hub and spoke' geometry, with a few key nodes, or hubs, with a large number of connections, whereas the majority of nodes have a smaller number of connections to other nodes. This would imply that across a landscape, the larger wetlands might serve as hubs to maintain ecological functionality even when the smaller wetlands are lost or the links are disconnected (e.g., during the dry season). Therefore, the loss of the most highly connected wetlands would prove detrimental to the overall ecological functionality of the landscape. Wetland connectivity has been shown to follow a power law pdf, but temporal dynamics of hydroclimatic forcing alter the size and degree of connectedness of the wetland networks, as seen in the changes of the node–degree pdf (Fortuna et al. 2006; Wright 2010).

2.11.2.3 Wetland Dynamics

Natural intra- and interannual variations in hydroclimatic forcing control the wetland area pdf and network connectivity over time. Liu and Schwartz (2011) simulated the century long (1910–2001) temporal dynamics of water-area frequency distributions in the prairie pothole landscapes in North Dakota (**Figure 4**). This time line included the decade (1930–40) of the Great Dust Bowl drought and the more recent (1993–2001) floods, along with strong interannual fluctuations in precipitation. Several features of their simulations are of interest: (1) the area–frequency plots follow power law distributions, which suggest that the wetland distribution across landscapes has fractal (scale-invariant) spatial patterns, albeit with different slopes (i.e., spatial organization and connectivity) for different time periods; (2) starting from the predrought dry conditions in summer of 1928, the area–frequency plot lines shift steadily downward during the Dust Bowl decade as the landscape dries out, but the slopes of the pdfs over time are essentially the same, suggesting that while the total number of wetlands across the landscape was decreasing, their relative frequency distribution remained essentially constant; and (3) starting in 1992 summer before the deluge, the area–frequency plots gradually shifted upward (as the number of wetlands filled with water increases), but with a disproportionate increase in the number of smaller wetlands (increasing slope).

A wetland network with hydrologic connectivity (surface water and/or groundwater) among individual wetlands expands with increasingly wet conditions. But, as the wetlands dry out, the larger wetlands persist, albeit at lower water levels, and provide important ecological refuges during the dry seasons for mobile organisms. This implies that the changes in hydrologic network topology and spatial organization of water area are different during wetting and drying cycles. The outcomes within a wetland network as a result of stochastic hydroclimatic forcing will be nonlinear and path dependent (i.e., wet-to-dry or dry-to-wet), whereas the pattern and connectivity of wetland size distribution are affected by the water storage capacity within the landscape (Shook and Pomeroy 2011).

How does the loss of wetlands and their connectivity impact aquatic habitats and their integrity? Do the smaller more dynamic wetlands play a more important role compared to the larger more persistent wetlands? Species restricted to fixed and islandlike habitat types would be expected to be particularly vulnerable to extinction if their local and regional climate change as the habitat quality and connectivity change or as the current synchronicity between reproductive cycles and the hydroperiod shifts because of altered rainfall patterns. Changes in the spatial distribution of wetland habitats can reduce connectivity among communities and populations (as with habitat loss) or disturb patterns of diversity and adaptation that have developed over evolutionary history (e.g., gene swapping, invasive species). Similarly, rapid changes in the variability experienced by wetlands can have immediate consequences for species diversity and population persistence. The isolated nature of many freshwater wetlands, especially those in human-fragmented landscapes, may mean that many of these species will rely on in situ evolution to cope with the induced habitat changes. Anthropogenic land use changes can occur at short temporal scales (even weeks). Thus, biodiversity changes reflect the dominant role of specialization induced by direct or indirect anthropogenic forcing, whereas selection for plasticity might play an important role over the long term in adapting to climate change.

2.11.2.4 Loss of Resilience: US Case Study

Wetlands, historically viewed as wastelands, were drained in many locations worldwide (Mitsch and Gosselink 2007). As European settlers arrived in the United States, they began to cultivate the land and develop intensive agricultural practices. In time, the largest wetlands were the first to be drained through the installation of major canals and ditch networks. The expansion of croplands and extension of the drainage networks over time lead to the loss of wetland connectivity because of the drainage of increasingly smaller wetlands. These patterns of increased population, industrialization, and prosperity, which in turn drive the need for increased food production and expanded urbanization, have occurred in many countries, contributing to global-scale losses of wetlands over the past century.

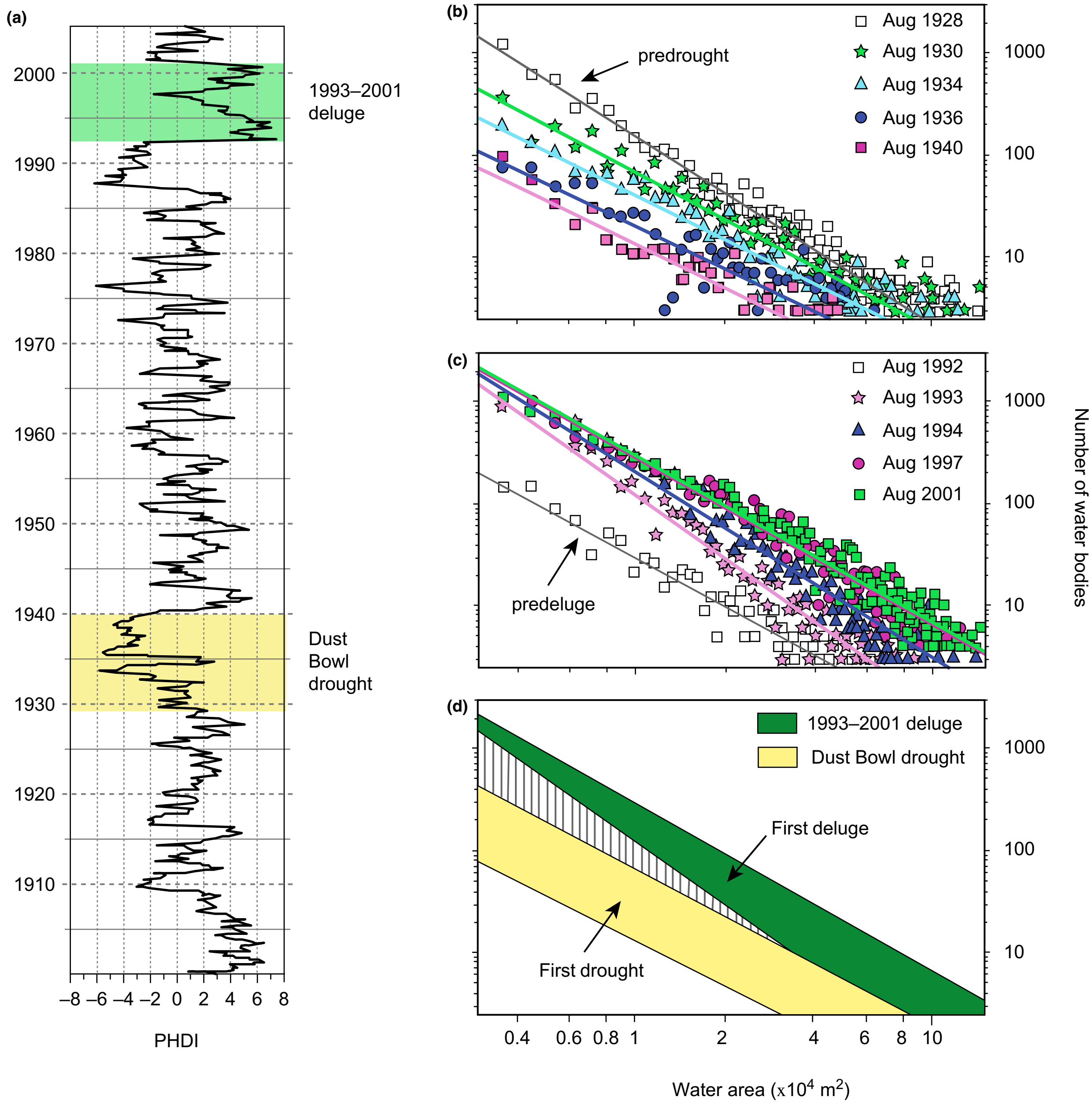

Figure 4 (a) Time series of Palmer hydrological drought index (PHDI) for the Prairie pothole region in North Dakota. Water-area frequency distributions for wetlands during (b) 1930–40 during the Dust Bowl drought and (c) 1993–2001 during the deluge, and (d) summary envelopes showing the variability in wetland size distribution resulting from hydroclimatic extremes. Source: Liu, G. M., and F. W. Schwartz, 2011: An integrated observational and model-based analysis of the hydrologic response of prairie pothole systems to variability in climate. *Water Resour. Res.*, **47**, W02504.

The resilience of fractal wetland networks is highly vulnerable to the loss of keystone wetlands that serve as ecological hubs or as nodes that serve as vital connectors for flows of water, solutes, and energy. Because of the connectedness of wetlands in a larger complex network, the short- and long-term connectivity dynamics have important ecological consequences in terms of species dispersal and persistence. Such consequences result from inter- and intraannual changes in hydroclimatic forcing (e.g., rainfall patterns), aquatic vegetation dynamics, and anthropogenic forcing (e.g., LULC changes).

The spatial organization of wetlands across a landscape also determines the mean distance between wetlands (i.e., the connectivity of patchy habitats). Thus, removing certain wetlands could significantly increase the mean distance between adjacent wetland habitats (as well as the statistical distribution of distances), which would alter the overall functionality and ecological resilience of the landscape. For example, in the Carolina Bays, if all wetlands smaller than 1.2 ha were removed, the average distance between nodes would rise from ∼470 to ∼670 m (Semlitsch 2000). If this increased distance to habitats is larger than the dispersal range of certain aquatic species, their life cycles would be significantly disrupted, leading to the loss of biodiversity.

Wright (2010) assessed the connectivity of a prairie pothole network as the distances between the centroids of wetlands that are equal to or smaller than the dispersal distance of an aquatic organism. That is, if the spatial distance is smaller than the distance that an organism can reach, two wetlands are assumed to be ecologically connected to each other. Therefore, loss of wetlands within a network decreases the probability that the organism can move to an alternative refuge if its current habitat dries out, either due to anthropogenic drainage or due to the duration of the natural hydroperiod. However, not all the wetlands nodes removed cause the same degree of loss for dispersal probability. A node may have a number of neighboring nodes of similar distance, which may act as alternate refuges. If these neighbors are connected, alternate pathways will allow detouring after the node is removed.

Two attributes of wetland networks are important from an ecological perspective: *clustering coefficient* and *centrality*. The property of the connectedness between neighbors is measured as the clustering coefficient or redundancy (Newman 2010). On the other hand, a network node may act as a critical transit point to numerous key species. *Centrality* is a measure of the importance of a specific node in a network; it defines the number of shortest paths that pass through that node, facilitating connections to other nodes in the network (Newman 2010). Removal of a node with high centrality would result in a significant loss of connectivity among network nodes and thus lead to habitat fragmentation, reducing the ability of aquatic plants and organisms to disperse. Therefore, we expect that the loss of nodes with high centrality would contribute to significant loss of certain ecological functions, even though the loss of the associated hydrologic function may be trivial. The removal of critical links leads to the isolation of small clusters from a large network. Gimmi et al. (2011) documented how typical wetland animals with dispersal distances of 0.3–1 km were historically constrained into fragmented habitats and showed that the number of species was reduced by the collapse of a largely connected wetland into medium and small isolated habitats. Such network analysis would provide clear metrics for identifying the gap that the loss of a single wetland leaves in the overall functioning of the landscape and can allow for better planning and design of constructed wetlands or the restoration of degraded wetlands.

2.11.3 Wetlands: Functions and Services

2.11.3.1 Flood Control

Wetlands provide depression storage for surface water and thus regulate the precipitation excess that contributes to runoff and recharge. Vegetation also increases surface roughness and as such serves an important role in slowing the rate of water flow across the landscape during flood events (Williams et al. 2012). Thus, removal of numerous wetlands within a landscape will result in loss of surface storage and increased runoff, while groundwater recharge rates and water quality decrease (Plocher and Levin 2003). This emphasizes the fact that even small wetlands play a significant role within the larger context of flood prevention utility provided by the wetland network.

Changes in flood patterns can be particularly damaging to urban communities (increased flood risk) and to wildlife that depend on stable hydroperiods. A shift from flood-dominated wetlands to a drained landscape also presents problems for native species, as the altered system may be better suited to invasive species (Pringle 2001). Loss of riparian wetlands and conversion of landscapes for intensively managed croplands and urban areas have contributed to increased intensity and frequency of floods in the Mississippi River Basin (Olson and Morton 2012). These examples exemplify the role that wetlands play in protecting ecosystems and urban settings, which become increasingly vulnerable to extreme hydroclimatic events when wetlands are lost. With the possibility of changes in frequencies of floods and droughts, the loss of wetlands only exacerbates the adverse impacts experienced by human communities and aquatic species that depend on wetland functions.

2.11.3.2 Biogeochemical Filtering

Wetlands act as filters for water quality improvement by reducing the export of sediments, nutrients, and other contaminants to downstream aquatic ecosystems. The loss of wetlands represents a loss in the buffering capacity of the landscape to mitigate anthropogenic impacts, and directly contributes to increases of solute loads exported from the landscape, impaired water quality, and reduced habitat integrity. The effects of wetland loss are particularly evident in the corn–soybean belt in the Midwest United States. The conversion of a mosaic of erstwhile prairies, forests, and wetlands to monoculture croplands and intensive animal production (e.g., concentrated animal feeding operations) has contributed to dramatic increases in exported loads of nutrients (N and P), pesticides, pathogens, and other contaminants (e.g., hormones, veterinary pharmaceuticals) to receiving water bodies. The impacts of intensive agriculture have affected aquatic ecosystems at all scales, with the persistent, large-scale coastal hypoxia in the Gulf of Mexico one of the most notable impacts (Diaz and Rosenberg 2008; Kemp et al. 2009; Rabalais et al. 1996, 2002; Smith et al. 1999). Similar hypoxia is noted in many other coastal waters all over the world. The World Resources Institute has identified 415 locations around the world as experiencing eutrophication to some degree, 169 of which are hypoxic (Selman et al. 2008). Such widespread examples of water quality degradation show that the removal of wetlands causes significant unintended consequences for downstream ecosystems through the alteration of hydrological and biogeochemical cycles.

2.11.3.3 Ecological Habitats

Ecological functionality of wetlands networks are largely driven by complex interactions among external forcing (natural and anthropogenic) on the landscape features, hydrologic dynamics within and among nodes, biogeochemical efficiency in nutrient processing, and the ecological responses of resident populations and species. Both short- and long-term changes in hydrologic connectivity, habitat quality and integrity, and the spatial distribution of wetlands within the landscape can result from acute and chronic shifts in external forcing and internal feedbacks. The persistence of biodiversity and resilience of wetland communities are impacted by the interdependence of forcing and hydrologic and biogeochemical responses of landscapes. Thus, two dominant attributes of wetlands as ecological habitats are relevant to our considerations here: structure (form) and ecological services (functions). In particular, the hydroperiod (intraannual variability) and the vegetation composition are key features that determine the habitat suitability and integrity. High-temporal variability in structure is essential in some cases for the persistence of certain species, while temporal stability of structure is needed for the persistence of other species. Thus, the hydroperiod plays a key role in the maintenance of habitat and species diversity.

Wetlands provide a highly structured, nested spatial context that shapes the composition of resident communities and the evolutionary trajectories of the organisms that inhabit them. This spatial structure influences the distribution and abundance of organisms at multiple scales, ranging from the organization of wetland features across a landscape to the distribution of microhabitats within individual wetlands. The association between organisms and specific ecological conditions generates high levels of community and population structuring within patchy habitats, and the extent of 'connectedness' among suitable habitats has fundamental implications for the distribution and maintenance of species diversity (MacArthur and Wilson 1967) and population persistence (Hanski 1999; Levins 1970).

Wetlands are not only structured and connected habitats for a broad range of organisms, but can also serve as population sources and sinks or stepping stones for dispersing individuals. Small and isolated wetlands have the largest potential to serve as stepping stones in a wetland network, allowing connections to more distant wetlands in otherwise fragmented smaller wetland clusters. Without such nodes, both the density and types of individuals migrating will diminish as dispersal distances become too great for some species (Semlitsch 2000). This can create wildlife population sinks: isolated locations where mobile species take refuge when most or all other options are unavailable. Such areas are created when too much habitat is lost and/or connectivity to other habitats is destroyed. Refugee species persist in the remaining viable habitat(s), living on what resources are available within the sink. Initially, the collection of refugee species leads to a population boom (Pringle 2001). However, these sinks are detrimental to the local ecosystem, as refugee species put a strain on local species and consume resources. Once the sink location is exploited of resources beyond its carrying capacity, the refugee species will endure a subsequent population bust (Pringle 2001).

2.11.3.4 Economic Benefits of Wetland Services

Wetlands worldwide are frequently drained to create suitable cropland and urban settlements with tightly managed hydrological regimes and ecological properties. The immediate socioeconomic benefits of increased land area for food production often outweigh the hydrological, biogeochemical, and ecological benefits that can be obtained from wetlands. Significant benefits provided by wetlands are usually overlooked, including their key direct and indirect contributions to food and water security. Direct uses of wetlands for food include protein sources such as fish, grain sources such as rice paddies and fodder for farm animals, as well as a source of drinking water. It is estimated that rice paddies feed half of the world's population, a highly significant source of nutrition that otherwise cannot be met. Many cultures utilize wetlands as sole protein sources, as isolated wetlands may provide the only hospitable habitat for fish and other animals (Abbot and Hailu 2001).

In countries with high intraannual precipitation variability, wetlands provide bursts of food services that can be used to maintain yearly food security. For example, corn and other vegetables are often cultivated using water from wetlands in countries with high intraannual precipitation variation. The rainy season provides precipitation necessary to facilitate crop growth. Food becomes ready for harvest once the dry period begins providing essential food products that can sustain the population through the dry season. Such wetlands also serve as essential sources of drinking water, especially when water levels are sustained throughout the year (i.e., hydroperiods are long) (Abbot and Hailu 2001).

As wetlands are continually drained to create efficient large-scale agriculture and urban settlements, numerous beneficial services are lost. Nutrients and pesticides applied to intensively managed croplands or urban areas (i.e., lawns) are transported to nearby receiving water bodies during storm events, impairing groundwater and surface water quality. Herbicides, such as atrazine, can have long-term ecological health effects, especially for sensitive aquatic species, and increase the need for water purification to protect public health. Sensitive aquatic species (i.e., fish) can be adversely affected in watersheds that are impacted by intensive agricultural practices (Durhan et al. 2006; Leet et al. 2011; Smith et al. 1999; Soto et al. 2004), sometimes leading to localized and regional species population collapse and unforeseen food web alterations. As such, wetland ecosystems unable to endure perturbations can become damaged irrevocably, potentially leading to decreased availability of protein sources (such as fish) and loss of other components of the food web.

In some cases, services once provided by a wetland may never be fully recovered. The loss of vital protein sources as well as water filtering and nutrient processing are perhaps the most dramatic causes of degraded food and water security. As monoculture crops are unsustainable in the long run due to the corresponding loss of landscape resilience, it is important to preserve as many natural wetlands as possible. Removing nodes especially based on size and location without knowledge of connectedness to the network will lead to continual ecosystem degradation and species collapse.

Indirect contributions to food and water security come in the form of economic advancement. As with the harvesting of corn and other vegetables, many localized crafts are dependent on wetlands, particularly in rural communities. Baskets may be fashioned from reeds and sold in order to make money, which can be used toward the purchase of food. Farm animals graze on wetland vegetation and thus serve as both a direct source of protein and an indirect source of food through meat and dairy sales. Even medicinal plants are harvested and sold (Abbot and Hailu 2001). Because of the various ways in which wetlands contribute to food security and economic well-being, organizations are calling for effective management of wetlands in order to sustain and expand the role wetlands play.

Ecotourism, rising in popularity, is another indirect link to food and economic security. As wetlands grow in popularity as places to learn and relax, revenue generated by tourism can be used toward economic stability and food security. A positive facet of ecotourism is that revenue is generated without the extraction of resources from the wetlands. On the other hand, too much tourist traffic can lead to overall degradation of the wetland in terms of ecological benefits, viable habitat space, water quality, and scenic value (Mitsch and Gosselink 2007).

2.11.4 Policies to Prevent Wetland Losses: US Case Study

The initial political recognition of wetland degradation in the United States occurred in 1977 when Executive Order 11990 was signed, which sought to encourage agencies to minimize their negative impacts on wetlands. Twelve years later, the No Net Loss of Wetlands policy was endorsed (Turner et al. 2001). In addition, Section 404 of the Clean Water Act that contains provisions for wetland mitigation was updated in 2008. The goal of the No Net Loss policy was to replace or restore an equivalent spatial area of wetland for every wetland lost due to alteration or destruction. Different types and sizes of wetlands serve unique roles in the larger landscape. With the No Net Loss policy, there are no formal guidelines stating the proportion of wetland sizes to be replaced; the Environmental Protection Agency (EPA) generally follows a 1 ha destroyed to 1 ha created metric. In practice, this allows the creation of a single large wetland to replace multiple smaller wetlands, as long as the total area replaced is equivalent to or greater than the destroyed area.

Wetland replacement on a one-to-one area basis is not ecologically or hydrologically equivalent, when several small wetlands are replaced by one large wetland. In particular, Turner et al. (2001) found that among four states surveyed, only about 70% of the total destroyed wetland area had been recovered or replaced. This does not account for functional replacement, which is typically only about 20% of original wetland losses. Vegetation cover is generally the largest metric used to determine wetland health. This metric alone does not begin to address many key functions of wetlands, thus causing the reduction in realized functional recovery (Windham et al. 2004).

According to the US Department of Agriculture, the No Net Loss policy has been quite effective, with approximately 250 000 acres of forested wetlands developed between 1998 and 2004 (Dahl 2006). This acreage is larger than the total wetland acres lost during that time period, thus allowing the National Resource Conservation Services (NRCS) to deem the No Net Loss policy successful. Although this claim of success is true for recent times (i.e., since 1998) on an area basis, it ignores the effects of size, location, and distribution of wetlands on overall wetland services and ecosystem health. Furthermore, large-scale losses prior to the enactment of this policy are not addressed in this positive assessment.

The EPA and Army Corps of Engineers created the National Wetlands Mitigation Action Plan in 2002, which outlined the methods of compensatory mitigation for wetland replacement and creation, stating that restoration, establishment, enhancement, and preservation are all vital elements of wetland policy. Gains in wetland functions are desired but not necessary to meet permit requirements. Mitigation types are not recorded by the US Army Corps permitting districts, making functional restoration difficult to evaluate (Wilkinson and Thompson 2006). Furthermore, permits issued for wetland reclamation and creation can go uncompleted or fail to be issued, and the timelines for efficacy assessment typically do not extend 5 years (Turner et al. 2001; Windham et al. 2004). Adequate placement, extended monitoring metrics and timelines, and standard permit enforcement would be a start toward solving the problem of ineffective and inadequate restoration and recreation of wetlands. In addition, food and water security and long-term landscape resilience must be added to the discussion, enabling policy leaders to understand the functions and roles of wetlands in society (Oneka 1999).

Policies and practices that lead to losses of wetlands during the past century were based on a lack of understanding of the interconnectedness of the landscape elements and coupling among landscape processes in maintaining landscape functions and overall resilience. Incremental changes at the local or regional scales were presumed not to be cumulative in time and failed to acknowledge that local impacts can propagate and amplify over spatial and temporal scales. Furthermore, the adverse outcomes of persistent and continually intensifying stresses on landscapes at regional and global scales were not fully appreciated until recently.

The fragmented nature of policies and regulations, often overlapping and sometimes contradictory, uncoordinated landscape management by multiple federal and state agencies, and scientific explorations disconnected because of disciplinary boundaries have all contributed to the continued degradation of wetland ecosystems from increasing anthropogenic stressors. An interdisciplinary approach to scientific investigations and an integrated systems approach to management are becoming increasingly common. Two essential features of the new paradigm are (1) considering the landscapes as coupled complex systems, such that essential features of form (size distribution, location, patchiness, connectivity) and critical functions are retained to maintain landscape resilience and (2) adaptive management that relies not on rigid plans, but incorporates flexibility and learning from sufficiently large restoration efforts to reduce uncertainties and adverse unanticipated outcomes.

2.11.5 Paths to Wetland Restoration

2.11.5.1 Managing for Resilience

Modern industrial agriculture is based on maximizing economic returns through increased crop yields and attempts to minimize risks of crop losses. Thus, land management practices are predominantly driven by increased efficiency and risk avoidance, just the same as other engineered industrial systems such as manufacturing. This pursuit of efficiency in agricultural landscapes has contributed to the loss of natural diversity and heterogeneity within the landscapes, causing functional homogeneity to emerge (Basu et al. 2010). Risk avoidance and efficiency maximization management strategies may increase the stability and predictability of complex systems, but decreased diversity and adaptive capacity make such engineered systems more vulnerable to unforeseen 'shocks' from external drivers. Park et al. (2012) proposed an improved management strategy – based on a blending of risk- and resilience-based approaches – for engineered complex systems, which is also suitable for landscapes dominated by wetlands.

The unintended consequences of engineering of landscapes are that (1) increased drainage efficiency (due to loss of wetlands and their water retention capacity) leads to flashier flow patterns, increased flood risk, and degradation of aquatic habitats; (2) hydrologic responses of agricultural catchments are dominantly controlled by hydroclimatic forcing because the spatial variations in soil–water deficits (created by evapotranspiration losses) are homogenized by monoculture crops; and (3) long-term, repeated fertilization contributes to the build-up of excess nutrient stores within soils and homogenizes the biogeochemical responses such that nutrient loads exported to receiving water bodies are controlled by discharge patterns. Each of these characteristics of an industrialized agricultural system managed for efficiency have significant implications for sensitive aquatic ecosystems, which are now much more vulnerable to shifts in hydroclimatic forcing.

Given the vulnerability of wetlands and the communities that depend on them for survival, landscapes need to be managed from a resilience perspective rather than from an efficiency perspective. Managing for efficiency has caused the loss of the natural resilience of landscapes, and therefore the potential for collapse of ecosystem structure and function is increased under some climate change scenarios. Efficiency-based crop production or urbanization must be traded for landscape management based on improved resilience. Two key features to restore are (1) structural and functional diversity, which in turn enhances the adaptive capacity of a system when confronted with low-probability high-consequence disturbances (e.g., droughts, floods) and (2) adaptive management, in which managers are flexible and able to cope with system diversity (e.g., diverse crops rather than monoculture cropping, with diverse management practices). That is, landscape management should not be optimized based on achieving the highest efficiency and stability; instead, the goal should be to optimize for sufficient diversity, variability, and adaptability for greater landscape resilience. However, managing for landscape resilience under the uncertainties of future climate is a major challenge. Strategies that aim to increase diversity (thus, enhance adaptability) are desirable but may not be sufficient; the Modern Portfolio Theory (MPT) can be used to optimize spatial allocation of resources either to achieve maximum conservation benefits for a unit of monetary investment for a given level of uncertainty or to minimize uncertainty given an expected level of conservation benefits (Ando and Mallory 2012).

2.11.5.2 Restoration Suggestions

Wetland restoration should start with an integrative approach. Understanding the underlying fundamental connections between hydrological, ecological, and biogeochemical factors greatly increases the chance for success of created and restored wetlands. Seeing wetlands as nodes in a complex network across a landscape enables scientists, land managers, and policy makers to better understand the consequences of wetland removal in addition to better monitoring the success of policies such as the No Net Loss policy. Wetland preservation must extend beyond the typical isolated location of importance (Amezaga et al. 2002). Both the size of a wetland and its location within the wetland network play a role in its ecological significance (Semlitsch 2000). Urban or constructed and natural wetlands possess different attributes because they are subject to differing climatic and physical alterations (Windham et al. 2004). As such, metrics for wetland restoration success should include distinctions for spatial organization, connectivity, and hydrologic regimes to further enable proper maintenance and care.

Urban wetlands produce a limited species pool, and thus generalized species cover is not a good indicator of ecosystem functioning for such wetlands (Windham et al. 2004). Hydrological and ecological connectivities have an important role in predicting wetland species richness and as such, should be a major component in policy formation and wetland restoration efforts. Placement among existing natural or constructed corridors (e.g., forest, meadow, etc.) is another key determinant of reaching the desired overall ecosystem health and species representation (Brown et al. 2012). While restoration of wetland hydroperiods is essential, improving habitat quality and connectivity to sustain species diversity is more important. Therefore, targeting restoration efforts to maximize the desired ecological, hydrological, and biogeochemical effects is perhaps the best solution to ensure successful implementation of policies such as the No Net Loss policy.

Because the large extent of damaged and modified wetlands has already passed tipping points, after which the restoration may be only partially revocable, it might be unrealistic to picture a restored landscape that fully serves ecologically favored functions in a short time frame. Moreover, changes in LULC surrounding wetlands will limit the full recovery of an altered landscape. These changes should be maintained at some levels to provide critical socioeconomic services. As there were once critical links that connected the now isolated clusters of wetlands, identifying the critical pathways that hydrologically and biologically reconnect these clusters will be an effective way for restoring a landscape.

2.11.5.3 Guidelines for Constructed Wetlands

Power law distributions, which emerge and are observed in numerous natural systems, indicate the ability of a system to self-organize when constantly pushed to a disordered state by natural perturbations (Barabási 2003). Also, the power law patterns are indicative of optimum diversity, which is critical for resilience. Anthropogenic forcing has modified wetland networks through removing nodes (wetlands) and links (connectivity among wetlands), resulting in a narrower range in variation of wetland sizes and connectivity.

Humans have changed wetland networks toward a state of decreased diversity and increased isolation. While bounded variation may serve efficient management for human purposes, the built-in rigidity will eventually lead to the systematic failure of hydrological, ecological, and biogeochemical functions that are maintained by self-organization and adaptation through the connectivity of wetlands. Thus, the construction and/or restoration of wetlands should strategically aim for allowing self-organization for the system as a whole and reducing the physical constraints (e.g., roads and settlements) that restrict ecological connectivity.

Understanding the interdependence and synchronicity of hydrological, biogeochemical, and ecological functions helps current efforts to mitigate the impacts on water quality and habitat suitability. An increased understanding of the role wetlands play in the overall ecosystem services provided by natural wetlands would present a unique opportunity to implement new standards for the design and implementation of constructed wetlands as best management practices, taking size, persistence, and connectivity into account. The resilience of wetlands is a function of hydrological, biogeochemical, and ecological connectivities clustering coefficient, centrality measures, and the role that wetlands of different sizes play in the overall functionality of the landscape.

As societies continue to seek socioeconomic progress, landscape efficiency is generally achieved at the expense of landscape resilience. However, socioeconomic progress and landscape resilience could be achieved simultaneously if vital wetlands within the landscape are protected and/or efforts are focused on understanding, quantifying, and restoring the functions of landscapes that had previously been sacrificed for socioeconomic gains. Constructed wetlands must be designed to optimize the various functions such that the original function of the landscape can be restored. The location of the constructed wetlands should be seen as an important design aspect to enable the constructed wetlands to play an important role in the connectivity of the overall landscape. Wetlands have the potential to serve important functions for increasing ecological and hydrological connectivities and the design and implementation of constructed wetlands should optimize these potential benefits beyond best management practices for nutrient removal. We envision that constructed wetlands could then be spatially targeted to maximize these beneficial functions while maintaining food security for generations to come.

2.11.6 Summary

Wetlands have evolved over millennia as self-organized and resilient elements of a landscape, which has been shaped by hydrologic and geologic forces. Stochastic hydroclimatic forcing strongly controls the spatial self-organization and connectivity of wetlands, and the temporal dynamics of the interdependent functions of the complex wetland networks. Aquatic species that depend on mosaic of wetlands as patchy habitats have also adapted their life cycles to the spatial organization and temporal fluctuations of the dynamic wetland networks. Rural populations, particularly in developing countries, continue to depend on the many services provided by freshwater wetlands, including food supply and drinking water. Persistent and increasingly dominant anthropogenic impacts – including increasing population, economic growth, freshwater appropriations, urbanization, and other direct and indirect impacts – have contributed to loss of about half of the freshwater wetlands worldwide, degradation of the remaining wetlands (OECD 1996), and loss of biodiversity through fragmented, isolated, and degraded aquatic habitats.

In urban communities, the loss of wetlands and the associated trading of ecological services for short-term socioeconomic benefits have enhanced food, water, and economic security and contributed to improvements in public health. However, such gains have undermined the ecological resilience of natural landscapes, and in the long term, will constrain the continual unsustainable practices in land and water management. Thus, urban food and water security in the long term are threatened by wetland degradation and removal. In developing countries, persistent connections to, and dominant dependence on, landscapes for provision of a mix of socioeconomic, cultural, and ecological services has reduced the socioeconomic resilience of the rural communities.

Restoration of degraded wetlands, as well as design and management of constructed wetlands, must recognize the importance of spatial organization, connectivity, and interdependence of wetland internal processes and functions. Thus, optimization for trade-offs among socioeconomic and ecological services without the loss of overall landscape and social resilience is essential for the long-term sustainability of food, water, and socioeconomic security.

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2.12 Food Security Implications of Climate Variability and Climate Change

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2.12.1 Introduction

The impacts of climate are evident on temperature and precipitation. For instance, global and regional land surface temperatures increased in the twentieth century, with the greatest warming in the last three decades (WMO 2005). The diurnal temperature range is narrowing in many regions across the world owing to the differential changes between daily maximum and minimum temperatures (Easterling et al. 1997). Significant changes have also been noted in climate variables (i.e., precipitation and air temperature) across the United States. Trends in observed precipitation suggest an increase in number of days with extreme precipitation during the twentieth century (Kunkel et al. 1999). An increase in mean air temperature was also reported (Karl et al. 1996). At the regional scale, Mishra et al. (2010) and Charusombat and Niyogi (2011) reported that precipitation, daily minimum air temperature, soil moisture, and runoff increased over the twentieth century, whereas daily maximum air temperature, ice content of the soil, and snow water equivalent experienced decline in Indiana and Illinois, and is expected to be a pattern that is true for the broader Corn Belt. Fall et al. (2011) and Martinez et al. (2012), however, show that the interpretation of trends in maximum and minimum temperatures is complicated by station sitting quality. As shown in Fall et al., poorly sited locations had an overestimate of minimum temperature trends and an underestimate of maximum temperature trends.

Some of these trends in climate variables (e.g., precipitation and air temperature) might persist under the future climate (Easterling et al. 2000; Sheffield and Wood 2007; Diffenbaugh et al. 2008; Diffenbaugh and Ashfaq 2010). Hayhoe et al. (2007) hypothesized an increase in annual air temperatures and changes in precipitation patterns in the future. However, although these projections provide a subset of plausible future regional climate, they do not cover all of the possible climate threats in the coming decades. This is why the bottom-up focus is needed with respect to climate risk.

For example, decreases in precipitation and increases in daily maximum air temperature in the coming decades could lead to persistent water stress conditions that could hamper crop production in the US Corn Belt. An occurrence of drought during the crop growing season often affects plant growth, crop yields, and in turn, food production. Increases in temperature and heat waves, as well as decreases in precipitation and snow storage, would further enhance the likelihood of drought occurrences. Globally, the impacts of drought and climate on crop yield and food production have been well documented in previous studies (Lobell and Asner 2003; Lobell and Field 2007; Mishra and Cherkauer 2010). Statistical as well as physics-based crop models predict that grain yield declines by 2.5–16% for every increase of 1 °C in seasonal temperature in the subtropics and tropics (Lobell et al. 2008; Battisti et al. 2009). Moreover, Schlenker and Roberts (2009) demonstrated nonlinear impacts of temperature on crop yields in the United States, showing that crop yields decline sharply when temperatures rise above 32 °C.

Historic drought events have had an observable impact on crop yield in the United States. Drought and heat waves caused about $145 billion damages to crop production across the United States (Lott and Ross 2006) during the last three decades. A 30% reduction in US corn production resulted from the drought of 1988 (Rosenzweig et al. 2001) and accounted for a loss of about $39 billion (Easterling et al. 2000). The US Corn Belt produces about 41% of world's corn and about 38% of world's soybeans (Schlenker and Roberts 2009), and is a major contributor of food aid to the African nations through the USAID program. The impacts of future climate, including interannual/decadal variability on US grain production, can contribute greatly to the uncertainty of future food production as well as to the efforts that are being undertaken to make the world more food secure. Climatic extremes such as droughts, floods, heat waves, and abnormally cold temperatures during the crop growing season undermine productivity and, in turn, crop yields (Funk et al. 2008; Lobell and Burke 2008; Battisti et al. 2009). This chapter provides a long-term (1915–2009)

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analysis of different climatic vulnerabilities such as drought, heat waves, and growing degree-days that might influence corn and soybean production in the US Corn Belt.

2.12.2 Methods

The author evaluated historic climate and its impact on corn and soybean yields in the US Corn Belt. The study domain is identified as the states that largely contribute to the production of corn and soybean as described in the National Agricultural Statistics Service (NASS 2009) (crop yield and plantation) data. This resulted in the selection of 13 states: Illinois, Indiana, Iowa, Kansas, Kentucky, Michigan, Minnesota, Missouri, Nebraska, North Dakota, Ohio, South Dakota, and Wisconsin.

Daily climate data, including maximum and minimum temperatures and precipitation, were obtained from the National Climatic Data Center (NCDC) for the period 1915–2009. The daily station data for the climate variables were then gridded (one-eighth degree spatial footprint) to remove spatial and temporal inconsistencies using the methodology presented in Hamlet and Lettenmaier (2005). To assess the impact of drought and heat spells on crop production in the US Corn Belt, the focus is on the reproduction and grain-filling period of corn and soybean crops (June–August, JJA), because this is the most sensitive period to climate extremes that adversely impact yields (Mishra and Cherkauer 2010). The author selected precipitation, maximum temperature (TMAX), minimum temperature (TMIN), standardized precipitation evapotranspiration index (SPEI) (Vicente-Serrano et al. 2010), and cumulative heat index (CUM_HEAT) for the grain-filling season to evaluate the impact of drought and heat spells on the crop yields in the Midwestern United States. Moreover, growing degree-days (GDD) were estimated for the entire growing season. The growing season for corn and soybean crops was estimated based on the start of the growing season (GSS) and the end of the growing season (GSE). To represent the impacts of extreme warm temperature, the CUM_HEAT was estimated for the grain-filling period during the crop growing season. The CUM_HEAT was estimated for each year as the cumulative temperature (sum of $\mathrm{TMAX_{day}}$–TMAX at 90th percentile) when daily maximum temperature exceeds the 90th percentile of the reference temperature (1961–1990). The SPEI was used to estimate droughts in the grain-filling season. The SPEI is similar to the standardized precipitation index (SPI); however, it accounts for the moisture deficit that could arise from evapotranspiration losses. Monthly SPEI was estimated between 1915 and 2009 for the grain-filling season. For this, a 3-month SPEI at the end of August (representing cumulative moisture conditions for the JJA period) was found suitable for the grain-filling period. Severe (SPEI: −1.3 to −1.5), extreme (SPEI: −1.6 to −1.9), and exceptional droughts (SPEI less than −2.0) can hamper the crop growth and yields.

The GSS and GSE dates for the corn and soybean crops were estimated following Qian et al. (2010). The GSS was defined as the day when the weighted mean air temperature has reached the minimum cardinal temperature ($\mathrm{CT_{min}}$, 10 °C, for corn and soybean crops) and remained above this temperature for five consecutive days. The GSE was estimated when the weighted mean air temperature reached $\mathrm{CT_{min}}$ (10 °C) and stayed below $\mathrm{CT_{min}}$ for five consecutive days. The weighted mean air temperature for each day was estimated using 5-day binomial smoothing. The GDD were estimated by summing daily mean temperature values above $\mathrm{CT_{min}}$ (10 °C) from GSS to GSE using the following equation:

$$\begin{aligned}&\mathrm{GDD} = \frac{T_{\max} + T_{\min}}{2} - \mathrm{CT_{min}},\ \text{and}\\&\mathrm{GDD} = 0\\&\text{if}\\&\frac{T_{\max} + T_{\min}}{2} < \mathrm{CT_{min}}\end{aligned} \tag{1}$$

Wavelet analysis was used to understand the temporal variability of the selected climatic indices. Wavelet analysis provides time variance of signal of any given time series of climate data (Torrence and Webster 1999). Wavelet analysis has been widely used and has become a tool for analyzing localized variation of power within time series (Torrence and Compo 1998). For the analysis, the Morlet wavelet was used (Torrence and Compo 1998; Torrence and Webster 1999). The wavelet power spectrum gives a measure of time series variance at each period and scale (e.g., 2–5 year) and each time (e.g., 1950–90).

The nonparametric Mann-Kendall trend analysis and composite analysis was adopted to evaluate long-term (1915–2009) climate variability. Mann-Kendall trend analysis is a nonparametric test; therefore, it does not rely on normality of the dataset. The composite analysis for extreme 5 years was used to identify the spatial variability associated with extremes of the selected indices. The first difference method was used (Lobell and Field 2007) for both crop yield and climate index to evaluate the relationship among them. The first difference method helps eliminate the effect of technology and other management-related factors on crop yields. The yield of any given year was subtracted from the next year and the difference was considered a contribution from climate variability. The first difference time series were regressed to understand the amount of the variability in the crop yield explained by the particular climate index. Regression analysis was performed between domain averaged crop yields and climate variables.

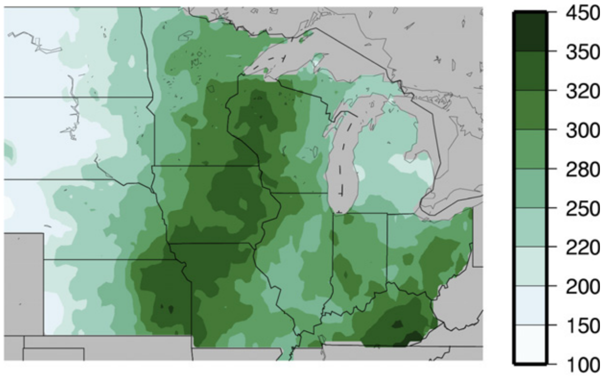
2.12.3 Results

2.12.3.1 Mean Climate during the Grain-Filling Season

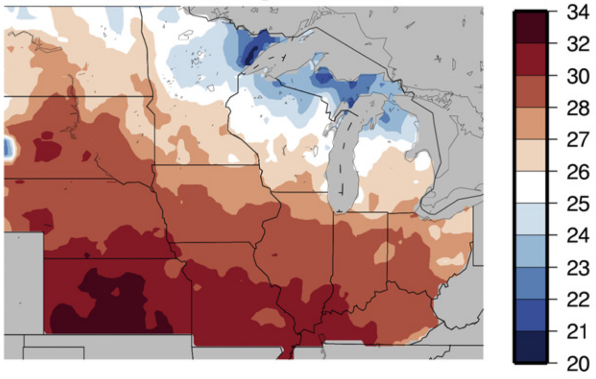
Figure 1 shows mean annual precipitation and maximum and minimum air temperatures for the entire Corn Belt during the long-term (1915–2009) retrospective period. During the grain-filling season (JJA), mean annual precipitation varied from 100 to 450 mm (Figure 1(a)). Mean annual precipitation is somewhat lower in the western part of the Corn Belt, whereas the central part receives higher precipitation during this season. Strong variability exists in mean annual maximum temperature along the north–south gradient of the Corn Belt (Figure 1(b)). For instance, mean annual maximum temperature is about 20 °C in the northern part of the domain, whereas it reaches up to 34 °C in some parts of the southern Corn Belt. Mean annual minimum temperature during the grain-filling season varies from 8 to 20 °C from north to south (**Figure 1(c)**). Results indicate that during the grain-filling season mean annual air temperature is higher than the 13 °C across the Corn Belt.

Temporal variability in mean annual precipitation, maximum and minimum air temperatures for the period 1915–2009 is presented in **Figure 2**. The domain average response of precipitation suggests that the Corn Belt region experienced some prolonged dry spells during 1930–36, 1970–76, and 1980–90 (**Figure 2(a)**). On the other hand, only a few above normal (precipitation anomaly >60 mm) events were found in the entire record of 95 years. The exceptional high precipitation event that occurred in 1993 caused significant flooding during the grain-filling season in the US Corn Belt. The long-term precipitation record suggests that mean annual precipitation for the grain-filling season has increased significantly (slope = 2.8 mm per decade, $p < .05$) during the period 1915–2009. Covariability of droughts and abnormally high air temperature is also evident from the long-term record (**Figure 2(b) and 2(c)**). For instance, during the two historic drought periods (1930s and 1988), the mean maximum and minimum temperature were higher than normal by about 2 and 1 °C, respectively. Dry conditions with hot spells pose detrimental impacts on crops as soil moisture depletes faster with high evapotranspiration loss in these conditions. Long-term trends suggest increases in minimum temperature with slight decline in maximum temperature during the grain-filling season. The Corn Belt region has experienced a significant increase in annual minimum temperature (slope = 0.07 °C per decade, $p < .05$); however, the trends in maximum temperature (slope = –0.06 °C per decade, $p > .05$) are not significant (**Figure 2(b) and 2(c)**).

(a) Precipitation (mm)



(b) Maximum Temperature (°C)



(c) Minimum Temperature (°C)

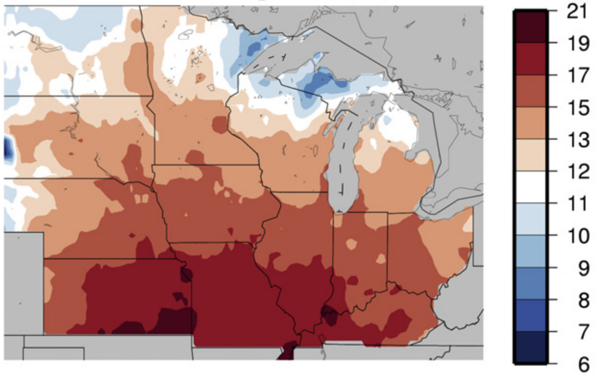


Figure 1 Mean annual precipitation, maximum and minimum temperatures for the grain-filling period (JJA) between 1915 and 2009.

Figure 3 shows spatial patterns of trends in precipitation and maximum and minimum temperatures during 1915–2009. Mean annual precipitation in the grain-filling season increased substantially (up to 14 mm per decade) in some parts of the Corn Belt (**Figure 3(a)**). Increases in mean annual precipitation are evident in the southern parts of Michigan, Wisconsin, and Minnesota and in the northern parts of Indiana, Illinois, and Iowa. Some areas within the Corn Belt also show a decline in precipitation; however, these reductions were not statistically significant. In general, for the US Corn Belt, an increase in precipitation favors crop growth and yields and provides sufficient moisture for a longer duration (depending on soil and other meteorologic conditions) that can satisfy the evapotranspiration demands of corn and soybean. Maximum temperatures have reduced by 0.10–0.30 °C per decade between 1915 and 2009 during the grain-filling season (**Figure 3(b)**). The reduction in maximum temperature is particularly evident in the central domain of the Corn Belt, and parts of this overlapped with the regions with increased precipitation (**Figure 3(a)**). Therefore, part of this cooling might be attributable to the increased cloud cover and evaporation from soils and transpiration from the vegetation in the region. On the other hand, the Corn Belt region has experienced somewhat consistent increases in mean annual minimum temperature during the grain-filling season (0.10–0.30 °C per decade) (**Figure 3(c)**). Increases in minimum temperatures and declines in maximum temperature might lead to no change in mean annual air temperature in the central part of the Corn Belt region. However, increases in minimum temperature in the northern part of the domain might provide better conditions for corn and soybean yields (**Figure 3(d)**).

2.12.3.2 Trends and Variability in Droughts

The author evaluated trends and variability in SPEI for 1915–2009 over the Corn Belt region (**Figure 4**). Precipitation variability helps provide the information about the abnormal dry or wet periods during the last 95 years. However, droughts often coincide with abnormal high temperatures that may result in higher evapotranspiration demands than expected. On the other hand, above-normal precipitation during the grain-filling season may attribute to cooling that can result in lower

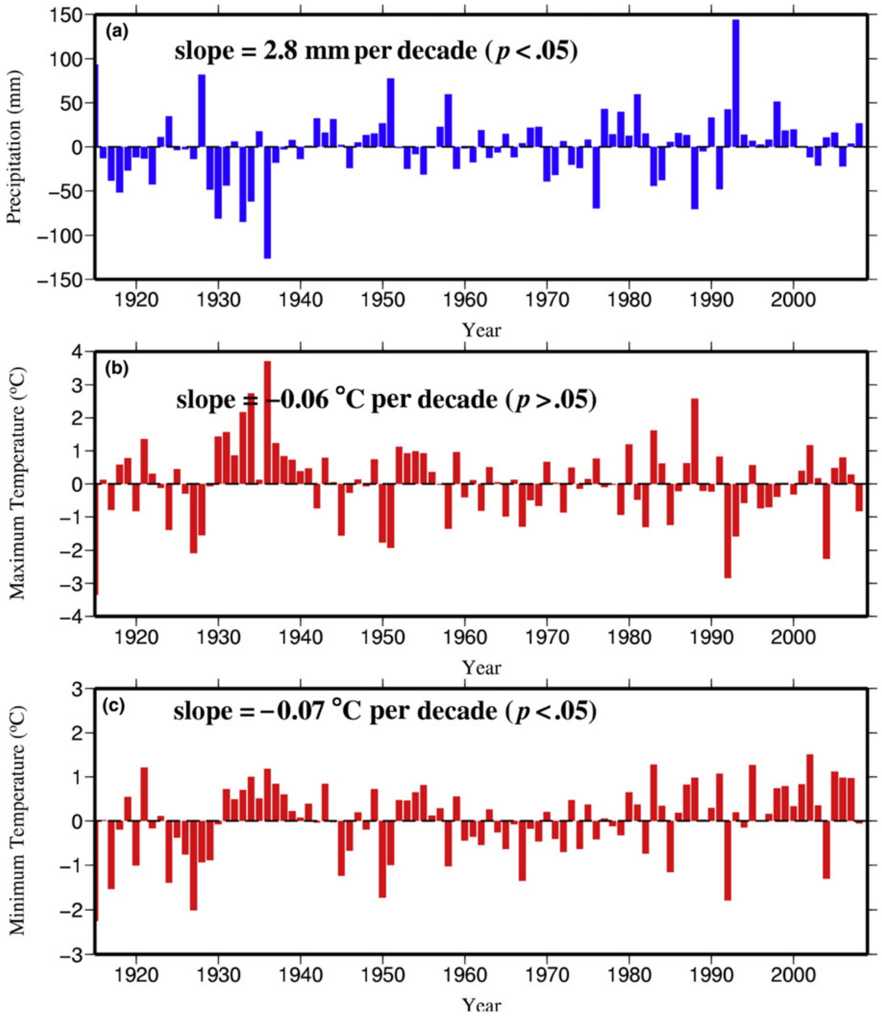


Figure 2 Domain averaged grain-filling season's precipitation and maximum and minimum temperature anomalies during the period 1915–2009. Anomalies were estimated by subtracting the long-term (1915–2009) mean from each variable. Trend slopes were estimated using the Mann-Kendall trend analysis with their statistical significance at the 5% level.

evapotranspiration demands. Because of high evapotranspiration demands, soil moisture depletes faster, which quickly translates into crop water stress. SPEI accounts for the role of temperature and therefore provides a useful measure for drought conditions during the crop growing season.

Extreme and exceptional (SPEI less than −1.6 and −2.0, respectively) droughts occurred throughout 1930–40 (Figure 4(a)). During extreme and exceptional droughts, major crop losses and sometimes entire crop damage can occur (Svoboda et al. 2002). Although the 1930s were abnormally dry, another major drought event in the Corn Belt region occurred in 1988 that severely affected crops. Abnormally high SPEI values indicate excess wetness that can be noticed in 1993 (Figure 4(a)). The 1993 flood event also adversely affected the corn and soybean crops. A positive trend in SPEI is observed which indicates that the region has experienced wetness during 1915–2009; however, the trends are not statistically significant at the 5% level. SPEI increased significantly in some parts of the Corn Belt during the last 95 years (Figure 4(b)). Increasing trends in SPEI were noticed in Illinois, Indiana, Ohio, Minnesota, Wisconsin, Michigan, Kansas, and Missouri. On the other hand, declining trends in SPEI were concentrated mainly in northern Wisconsin and the upper peninsula of Michigan.

The five most extreme drought events during 1915–2009 occurred in 1930, 1933, 1934, 1936, and 1988 (Figure 4(c)). The 1930s Dust Bowl period led the extreme drought events in the entire record. Moreover, all of these five drought events were extreme or exceptional in severity, suggesting that crop growth and production were affected severely during these events. Spatial variability of the drought composite for these five extreme dry years showed exceptional drought in southern Missouri, Illinois, Indiana, and Ohio. Moreover, parts of northern Minnesota and Iowa also experienced exceptionally dry conditions during these 5 years. During these extreme years, although most of the Corn Belt experienced extremely severe droughts, some areas in the southwest part of the domain were less affected (Figure 4(d)).

Figure 5 shows the wavelet power spectrum of SPEI during the period 1915–2009. Most of the variability in droughts was ranged between 2 and 5 years (Figure 5(a)). However, for some

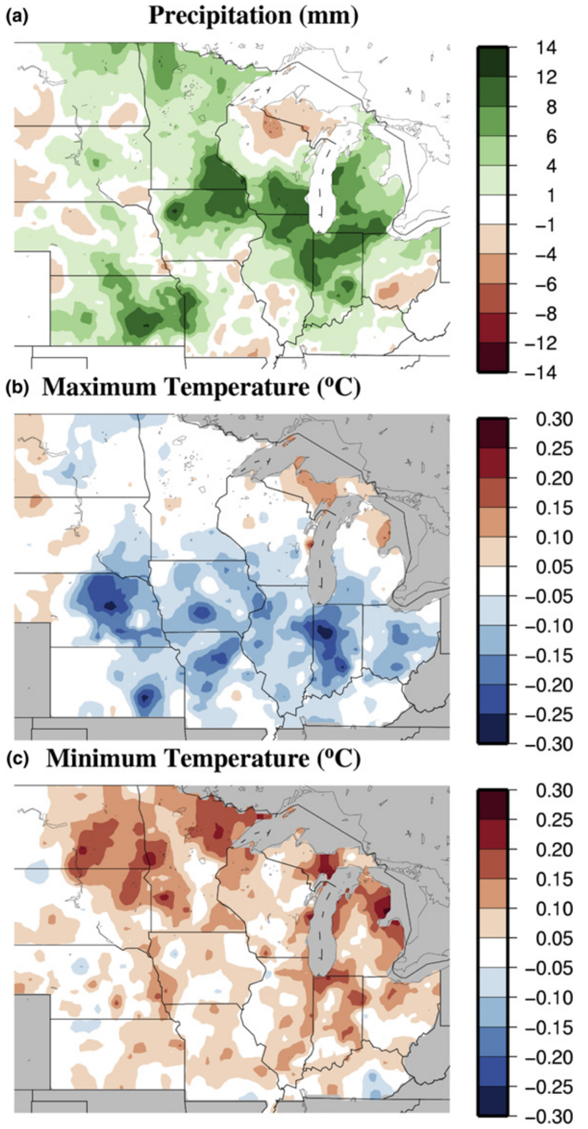


Figure 3 Decadal trends in precipitation, maximum temperature, and minimum temperature during the grain-filling seasons in the US Corn Belt. Trends were estimated for the period of 1915–2009 using the nonparametric Mann-Kendall trend method at a 5% significance level.

years (1950–60 and 1980–2000), a significant variability in the power spectrum was found in a 2- to 8-year period. The global power spectrum shows that most of the drought related variability in the Corn Belt lies between 2 and 5 years (Figure 5(b)). The variance in power was highest during the 1930s and 1988 (Figure 5(c)), whereas the period between 1940 and 1970 reflected low power variability.

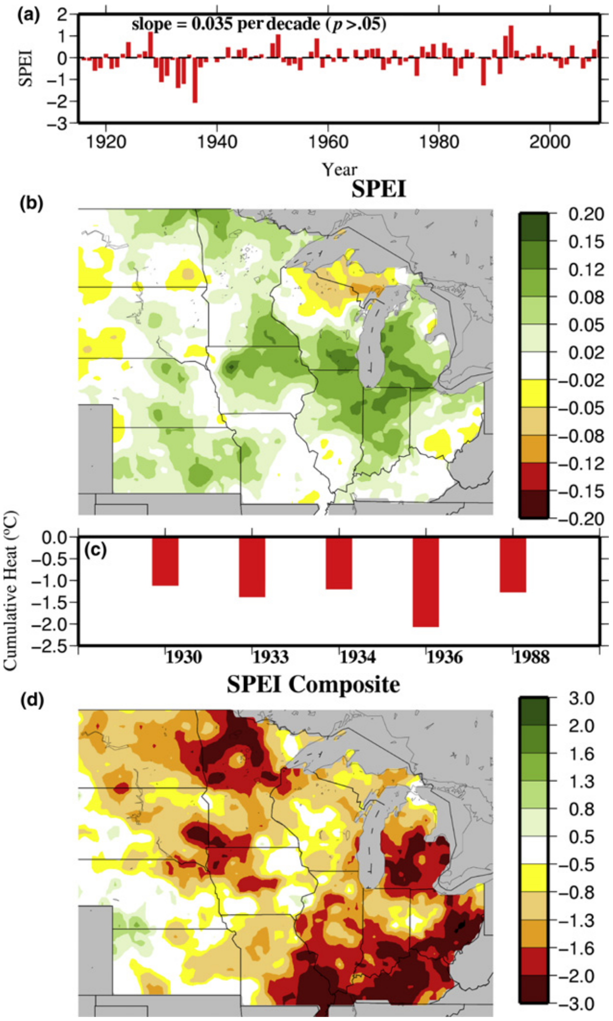


Figure 4 (a) Long-term domain averaged SPEI time series. (b) Spatial trends per decade in SPEI during 1915–2009. (c) Five most extreme drought years during 1915–2009. (d) SPEI composite of five extreme historic droughts.

2.12.3.3 Trends and Variability in Cumulative Heat

Cumulative heat during the grain-filling season provides the measure of heat stress for corn and soybean crops. The author estimated trends and variability in cumulative heat for the period 1915–2009 (Figure 5). The domain average cumulative heat for the Corn Belt highlights that the region experienced excessive heat spells during the 1930s (Figure 6(a)). Similar heat stress occurred in 1988, coinciding with the extreme drought. These results further demonstrate the concurrence of droughts and heat spells in the US Corn Belt.

Declining trends in cumulative heat were noticed during the last 95 years in the Corn Belt region. The declining trends (slope = −1.1 °C per decade, $p < .05$) in domain average cumulative heat were statistically significant during the period 1915–2009. Cumulative heat declined significantly in the central part of the Corn Belt region (Figure 6(b)). This portion of the Corn Belt also experienced a significant decline in maximum temperature and an increase in precipitation. Consistent with drought analysis, major heat spells occurred during the 1930s drought period. The top 5 years with the highest cumulative heat in the entire record of 1915–2009 were 1930, 1931, 1934, 1936, and 1988 (Figure 6(c)). All of these 5 years had cumulative heat greater than 30 °C. The cumulative heat was remarkably high during 1936 (cumulative heat ~150 °C). During the recent decade, the Corn Belt region

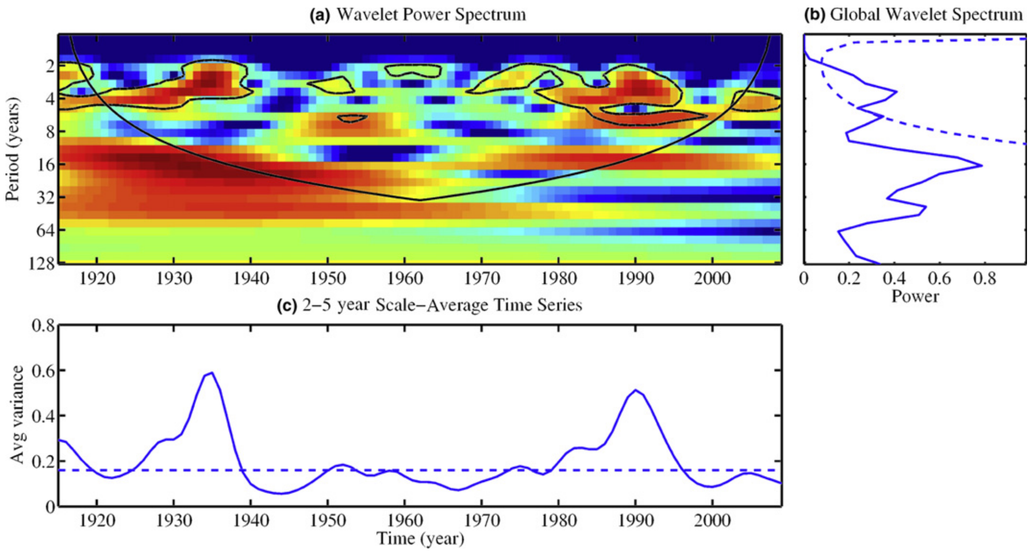


Figure 5 (a) Wavelet power spectrum for SPEI. (b) Global wavelet spectrum. (c) Average variance time series for a 2- to 5-year time scale. Contours in black show significant power, whereas blue dashed lines show the significant region at the 5% level.

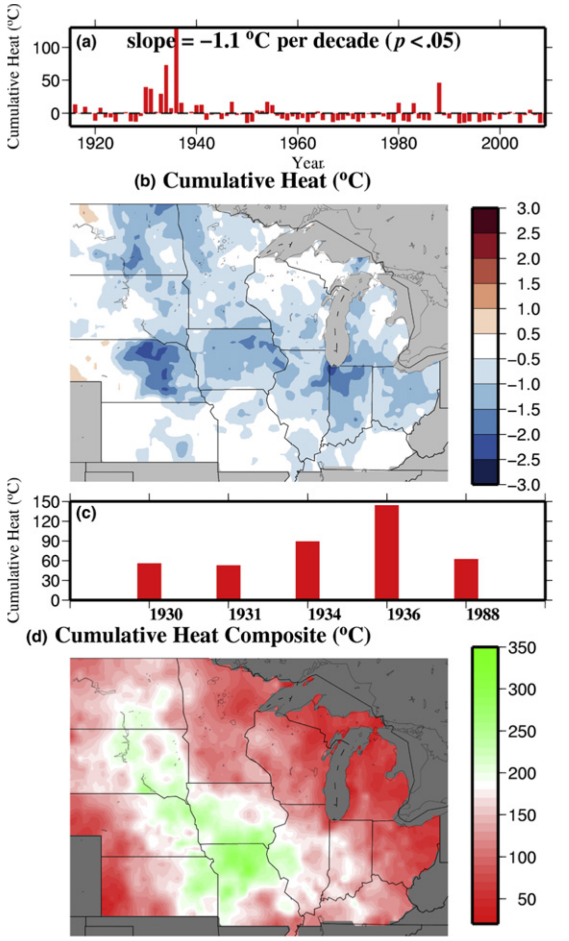


Figure 6 (a) Long-term domain averaged cumulative heat time series. (b) Spatial trends per decade in cumulative heat during 1915–2009. (c) Five most extreme cumulative heat years during 1915–2009. (d) Cumulative heat composite of five extreme historic droughts.

experienced high cumulative heat in 1988 drought during the grain-filling season. Composite analysis for the extreme cumulative heat years showed that cumulative heat varied between 50 and 350 °C. Although mean cumulative heat was between 40 and 100 °C for most of the Corn Belt, the cumulative heat peaked at greater than 300 °C in parts of Iowa, Missouri, Kansas, and Nebraska (Figure 6(d)).

The wavelet power spectrum for cumulative heat during the period 1915–2009 is presented in Figure 7. Wavelet power spectrum and global power spectra show that most of the variability in cumulative heat lies in the 2- to 5-year period (Figure 7(a) and 7(b)). Significant variance in power of cumulative heat occurred during 1930s and between 1980 and 1990. Both of these periods were influenced by ‘extreme’ and ‘exceptional’ droughts. The period between 1950 and 1980 showed the low variance in power of cumulative heat and therefore can be considered as a relatively heat spell-free period. Average variance in two extreme hot and dry periods (1930s and 1988) was significant; however, there was a substantial difference in the magnitude of variance (Figure 7(c)).

2.12.3.4 Trends and Variability in Growing Degree-Day

Growing degree-days (GDD) for corn and soybean crops during the period 1915–2009 are presented in Figure 8. GDD were anomalously high during the 1930s when the Corn Belt region experienced higher GDD by 200 to 300 degree-days above normal (Figure 8(a)). Other high GDD phases were noticed during 1920s, late 1950s, 1988, and late 2000. Between 1915 and 2009, GDD increased with a rate of 1.1 degree-day per decade; however, this increase in GDD was not significant at the 5% level.

Spatial trends in GDD suggested a substantial increase in the Northern domain of the Corn Belt region (Figure 8(b)). Remarkably, the northern part of the region experienced increases in GDD that varied between 5 and 35 degree-days per decade. These changes can be attributed to increases in the

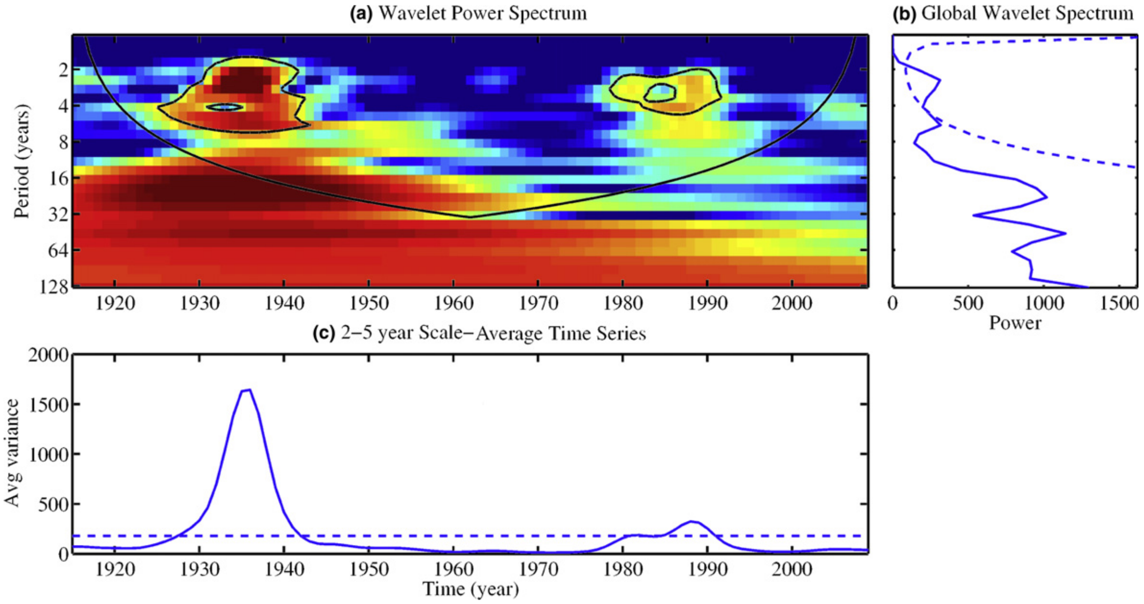


Figure 7 (a) Wavelet power spectrum for cumulative heat. (b) Global wavelet spectrum. (c) Average variance time series for a 2- to 5-year time scale. Contours in black show significant power, whereas blue dashed lines show the significant region at a 5% level.

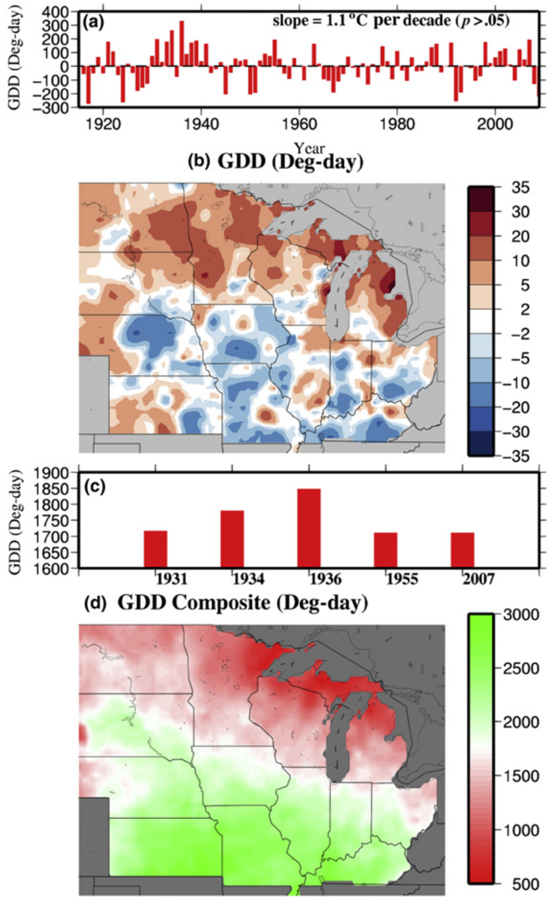


Figure 8 (a) Long-term domain averaged growing degree-day (GDD) time series. (b) Spatial trends per decade in GDD during 1915–2009. (c) Five most extreme GDD years during 1915–2009. (d) GDD composite of five extreme historic droughts.

minimum temperature in the northern part of the region. Increases in the minimum temperature might result in increases in frost-free period and therefore increases in the growing season length. On the other hand, declining trends in GDD in the central part of the Corn Belt region could be attributed to decreases in maximum temperature as well as increases in precipitation. The five largest GDD years for the Corn Belt region during the 1915–2009 period were 1931, 1934, 1936, 1955, and 2007 (Figure 8(c)). Similar to other variables, the author found that the five highest GDD years were largely outnumbered by the 1930 hot and dry period. Interestingly, the other major drought event (1988) was not recorded as the one with the highest GDDs. Strong North–South variability in GDD was found in the composite of GDD (Figure 8(d)). Mean GDD during the five extremes varied between 500 and 3000 degree-days. The GDDs were lower in the northern domain and higher in the southern part of the Corn Belt that can be attributed to differences in mean air temperature as well as the length of the growing season.

The wavelet power spectrum for GDD showed relatively higher variability in interdecadal time scales (Figure 9(a)). Similar to SPEI and cumulative heat, most of the variability in GDD lies in 2- to 5-year and 2- to 8-year time scales (Figure 9(a) and 9(b)). The significant variance in power of GDD was found for 1915–30, 1930–40, 1943–55, 1988–95, and after 2000 (Figure 9(c)). The period between 1956 and 1988 showed relatively lower variance in power of GDD.

2.12.3.5 Climate and Crop Yields

Figure 10 shows the variability in precipitation and the relationship of climate variables with the domain average corn yields during the period 1980–2009. Corn yields have increased historically, which can be attributed to improved management and technologic advancement, as well as

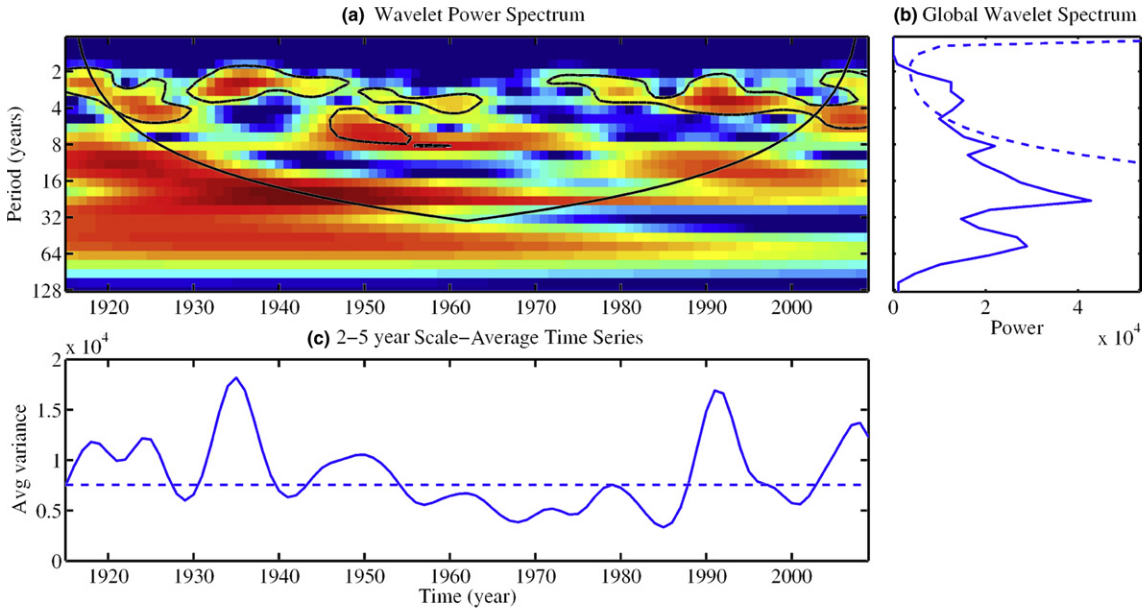


Figure 9 (a) Wavelet power spectrum for growing degree-days. (b) Global wavelet spectrum. (c) Average variance time series for a 2- to 5-year time scale. Contours in black show significant power, whereas blue dashed lines show the significant region at a 5% level.

improvements in seed varieties. To evaluate the climate impacts on corn yields, we selected the recent three decades, as the yields were somewhat less influenced by technology. Moreover, this period has two extreme years: the drought event in 1988 and the 1993 flood event (Figure 10(a)).

The variability in precipitation beyond one and two standard deviations severely affects corn yields (Figure 10(b)). For instance, the corn yields are very weakly related ($R^2 = 0.03$) to precipitation during the grain-filling season. In general, above-normal precipitation supports corn yields; however, the 1993 flood event (when the precipitation exceeded two standard deviations from the mean) adversely affected the corn yields. Because of the presence of this extreme flood event, the relationship between precipitation and corn yields became weaker. On the other hand, both maximum and minimum temperatures during the grain-filling seasons showed a stronger relationship with corn yields (Figure 10(c) and 10(d)). Above average temperatures during the grain-filling season lead to a reduction in crop yields. The SPEI that accounts for both deficits in precipitation and the influence of abnormal temperature shows better relationship with the corn yields than precipitation (Figure 10(e)). However, the cumulative heat showed the best relationship with corn yields (Figure 10(f)). However, GDD was weakly related to the crop yields (Figure 10(g)).

The relationship between soybean yields and climate variables is shown in Figure 8. Soybean yields are less influenced by the climate variability than corn yields. For instance, the influence of abnormal air temperature on soybean yields is substantially lower than those on corn yields. These differences can be attributed to the physiologic as well as phenologic dissimilarities in corn and soybean crops. The CUM_HEAT and maximum air temperature showed better relationship with soybean yields with coefficient of determination 0.34 and 0.27, respectively (Figure 11(c) and 11(f)). Among the fitted explanatory variables for corn and soybean yields, CUM_HEAT appears to be a better predictor than other climatic variables (i.e., precipitation, temperature, and GDD) in the United States.

The author also evaluated the multiple regression approach to estimate the change in crop yields owing to changes in the selected climate variables. From the stepwise regression, cumulative heat during the growing season explained most of the variability in corn and soybean yields during 1980–2009. The improvement in the coefficient of determination using the other variables (e.g., precipitation, TMAX, TMIN, SPEI, and GDD) was not statistically significant. One possible reason for this might be the degree of cross-correlation among the selected climate variables during the grain-filling season (Table 1). Cumulative heat during the grain- the author found that a 10 °C increase in cumulative heat in the grain-filling season leads to 6.2 and 1 bu per acre reductions in corn and soybean yields, respectively. A 10 °C increase in cumulative heat can be considered as 10 days with daily maximum temperature 1 °C warmer than the 90th percentile of the period 1961–90. Moreover, reoccurrence of a similar heat spell that occurred during the 1988 drought (cumulative heats were higher by about 50 °C than mean) may lead to 38 and 7 bu per acre reductions in corn and soybean yields, respectively.

2.12.3.6 Recent Climate Trends and Yield Impacts

To evaluate whether climate during the last three decades (1980–2009) has contributed to corn and soybean yields substantially, the relationship between crop yields and cumulative heat (Table 2) was used to identify the climate contribution (Figure 12). As the estimated loss in crop production is sensitive to the period of analysis (Lobell and Field 2007), the minimum 15-year period was used starting

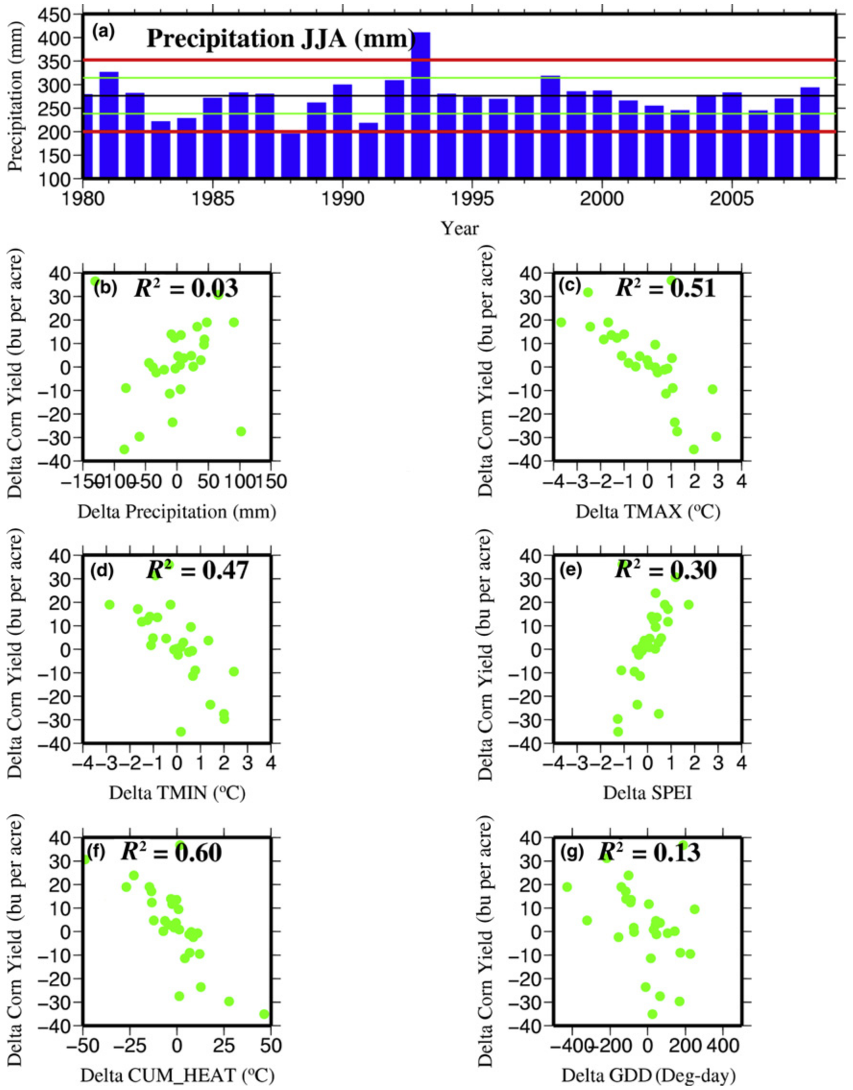


Figure 10 (a) Precipitation variability in the US Corn Belt region during 1980–2009. Red lines indicate two standard deviations from mean, and green lines indicate the range of one standard deviation from the mean, (b–g) relationship between change in climate variables and corn yield.

from 1980 with all possible ending years till 2009 (e.g., 1980–94, 1980–95, …, and 1980–2009). Changes in cumulative heat were used to analyze its impacts on crop yields using the regression relationship.

Impacts of recent changes in cumulative heat indicated a wide range of uncertainty in crop yields for corn and soybean (Figure 12(a) and 12(b)). However, the mean impact of changes was positive until 2000 for both the crops. After 2000, as reflected by the results, the 95% confidence interval of changes in yield showed both positive and negative values. The net impacts of climate on crop yields were largely positive for both corn and soybean crops, which can be attributed to possible cooling in the US Corn Belt.

2.12.3.6.1 Discussion and Conclusions

This chapter discussed climate and its influence on crop yields in the US Corn Belt. Long-term (1915–2009) analysis of climate (precipitation, maximum and minimum temperatures) and the selected climate indices reflected a wide range of variability in climatic trends that might have implications for corn and soybean production. There have been significant increases in precipitation and mean annual minimum temperature in the grain-filling season during the last 95 years. Results indicated nonsignificant cooling trends in mean annual maximum temperature during the period 1915–2009. Climatic trends influenced indices relevant to the crop production in the US Corn Belt. For instance, the frequency and severity of severe, extreme, and exceptional droughts seem to have declined but not been eliminated during the recent period. Although reduction in the maximum temperature was not statistically significant, it resulted in reduced heat stress during the grain-filling season. On the other hand, significant increases in mean annual minimum temperatures in the northern part of the domain have contributed to increases in growing degree-days. Consistent with trends in minimum temperature, more

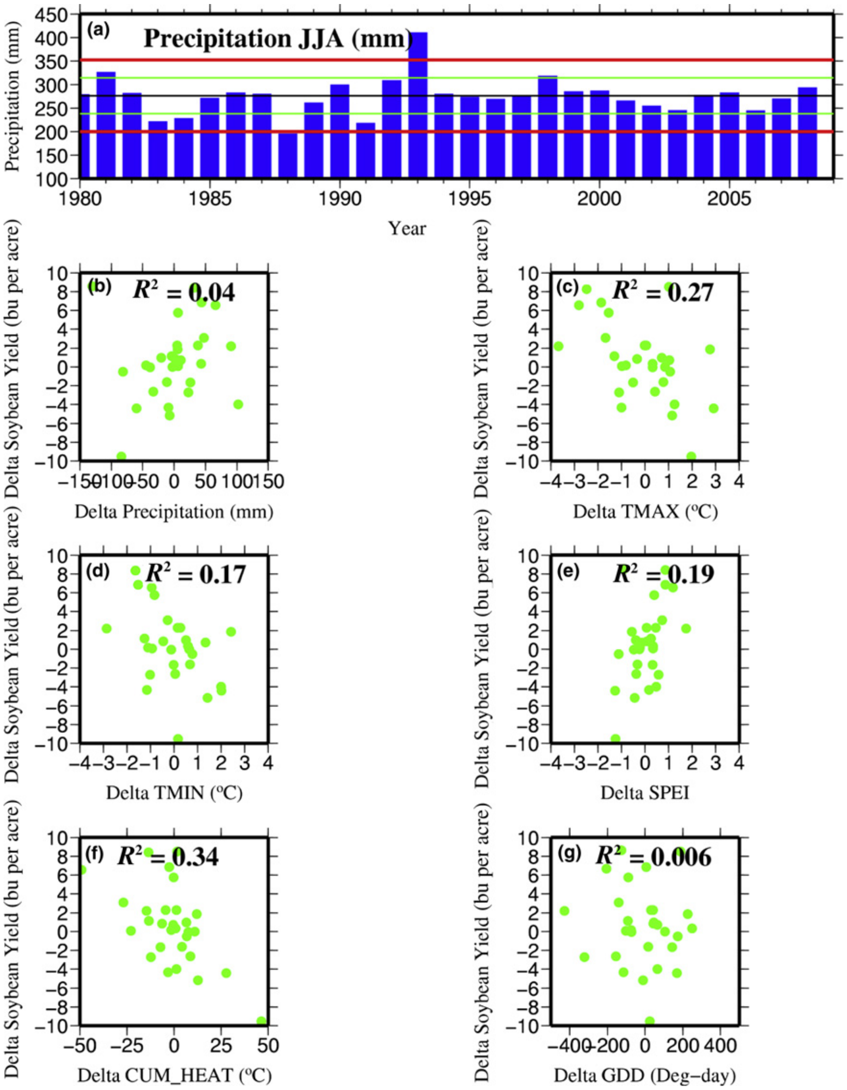


Figure 11 (a) Precipitation variability in the US Corn Belt region during 1980–2009. Red lines indicate two standard deviation from mean, and green lines indicate the range of one standard deviation from the mean, (b–g) relationship between change in climate variables and soybean yield.

Table 1 Correlations among climate variables during the grain-filling season

Variable	*Precipitation*	*TMAX*	*TMIN*	*SPEI*
Precipitation	1			
TMAX	−0.54	1		
TMIN	−0.19	0.9	1	
SPEI	0.88	−0.86	−0.67	1
CUM_HEAT	−0.58	0.78	0.54	−0.77

prominent increases in GDD were noticed in the northern part of the US Corn Belt. The trends in long-term climate with declining droughts, increasing precipitation, cooling of TMAX, increases in GDD in the northern domain, and declining heat stress in the central domain indicate more supportive climate for corn and soybean production in the US Corn Belt. Long-term analysis suggested that most of the extreme events (droughts and heat spells) occurred during the 1930s. The severity of droughts and heat spells that occurred during the 1930s remained unmatched in the last 95 years. For instance, four out of five most extreme droughts and heat spells occurred during the 1930s. The only event that fell in the five most extremes occurred in 1988. Drought severities and heat stress during the 1930s were about twice as high as those that occurred in 1988. Drought and heat stress during the 1988 grain-filling season severely affected corn and soybean production in the region. For instance, a 30% reduction in crop production was noticed during the 1988 drought (Rosenzweig et al. 2001). Reoccurrence of drought like that of the 1930s and 1988 could be even more detrimental for corn and soybean production. This is mainly because of increases in corn and soybean yields that the region experienced during the recent decades. This analysis shows that a similar heat stress to that of 1988 could lead to

Table 2 Linear regression relationships between crop yield and cumulative heat

Crop	*Intercept*[a]	*Slope*[a]	*Equation*
Corn	1.75 (−2.5, 6.0)	−0.8 (−1.0, −0.5)	Delta $Y = 1.75 - 0.8^a$ Delta CUM_HEAT ($R^2 = 0.60$, $p < .05$)
Soybean	0.38 (−0.9, 1.7)	−0.14 (−0.22, −0.06)	Delta $Y = 0.38 – 0.14^a$ Delta CUM_HEAT ($R^2 = 0.34$, $p < .05$)

[a] *Values in parenthesis indicate a 95% confidence interval.*

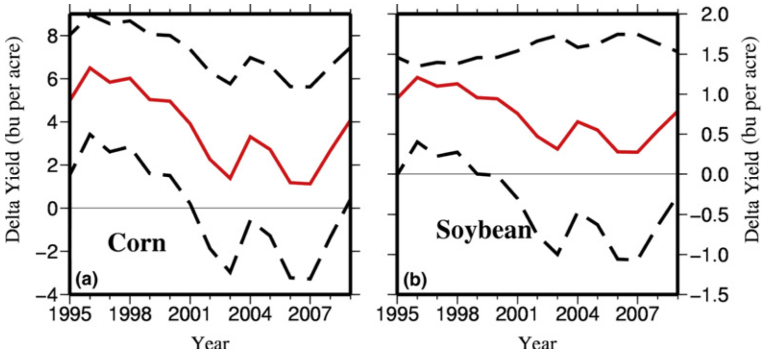


Figure 12 (a) Effect of climate on corn yields. (b) Effect of climate on soybean yield. The red line indicates estimates based on mean climate, whereas the black lines show the 95% confidence interval. Changes in cumulative heat were computed starting from 1980 until 2009, with a minimum of 15 years of analysis.

reduction of 38 and 7 bu per acre in corn and soybean yields, respectively.

Results indicate that the climatic patterns during the last 30 years have been largely supportive of corn and soybean production. However, increases in floods during the grain-filling season can severely affect the corn and soybean yields in the region. For instance, the 1993 flood caused $6–8 billion damage to farmers (FEMA 1995). Moreover, floods that occur in the early crop-growing season often delay the planting of crops, resulting in losses in crop yields. It was found that an increase or decline in precipitation more than one standard deviation from the mean affects corn and soybean crop yields dramatically (e.g., 1988 and 1993). These results are consistent with the findings of Rosenzweig et al. (2002), who reported a probability of events causing damage comparable with the 1993 flood will double by 2030 and quadruple by 2090. Further analysis is needed to understand the changes in probabilities of occurrence of floods and extreme precipitation events coinciding with the crop growing season in the US Corn Belt. More work based on regional climate vulnerabilities such as those owing to change in the frost patterns, early planting dates, and production practices are needed to better understand the impact of extreme events and potential reductions in crop production.

A strong covariance in climatic indices associated with drought, heat stress, and growing degree-day was found in the grain-filling season of the US Corn Belt. Precipitation in the grain-filling season reflected a weaker relationship with corn and soybean yields. In part this might be because of the 1993 flood event. During the 1993 flood, precipitation during the grain-filling season was two standard deviations higher than normal. The SPEI showed a stronger relationship than that of precipitation (SPI) and crop yields. Analysis of climate variables and corn and soybean yields suggested that cumulative heat during the grain-filling season can help explain the yield variability. However, the climate response on soybean yields is somewhat lower than that of corn yields.

Acknowledgments

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2.13 Assessing Vulnerabilities and Adaptation Approaches: Useful to Usable Tools

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2.13.1 Introduction

Global and regional climatic variability has the potential to cause impacts to agricultural operations around the world. For example, arid parts of the world could expand and serious constraints to crop cultivation are underway (Fischer et al. 2005). In other places, climatic shifts could create more potential agricultural land and better growing conditions if adequate soil nutrients also coexist (Fischer et al. 2005). However, the overall impacts of climatic stress may be negative and thus threaten global food security (Nelson et al. 2009). It is, therefore, critically important to assess farmers' vulnerabilities and capacities to respond to negative impacts of climatic stresses. To meet this challenge, there is a concerted effort around the world to both assess the vulnerability and adaptive capacity of farming households, as well as to better understand different ways to manage climate-related risk. This research suggests that one critical determinant of adaptive capacity of agricultural systems is the ability to use climate knowledge and decision support tools to inform preventive action and adaptation options to climate-related impacts.

This chapter reviews the literature focusing on the role of climate information use (or lack thereof) by farming households in shaping their adaptive capacity to climate impacts. It first reviews the empirical literature exploring the opportunities and constraints to use of climate information (especially Seasonal Climate Forecasts, SCFs) and how it may contribute to reduce the threat of climatic vulnerability to farming. It then discusses how this literature has assessed vulnerabilities and adaptation approaches and the social science research methods used. Finally, it concludes with an example of how social science data can be combined with climate modeling to reduce vulnerabilities and enhance adaptive capacities.

2.13.2 Vulnerability and Adaptive Capacity

The IPCC (2007) defines vulnerability as a function of a system's exposure, sensitivity, and adaptive capacity to climate impact; that is, vulnerability refers to "… the exposure and sensitivity of [a] system to hazardous conditions and the ability … of the system to cope, adapt or recover from the effects of those conditions" (Smit and Wandel 2006, p. 286). Adaptive capacity, in turn, is defined as "the potential or ability of a system, region, or community to adapt to the effects or impacts of climate change" (Reid et al. 2007, p. 612). (**Table 1** shows common determinants of adaptive capacity.) Hence, the vulnerability of farmers to drought, for example, depends on how exposed and sensitive they are to the event and how much capacity they have to respond and recover after it happens (IPCC 2007). The three dimensions of vulnerability – exposure, sensitivity, and adaptive capacity – are shaped not just by the magnitude and frequency of the climate event, but also by the timing and the multitude of deficits and capacities farming households have to cope with or adapt to climate stress. From this perspective, vulnerability is not a static concept, but varies

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Table 1 Determinants of adaptive capacity

Determinant	*Description*
Awareness	The ability to accurately identify the signals of change and their implications
Technology	The availability of and access to technologic options for adaptation
Resources	The availability of resources for adapting (including financial capital and physical resources)
Institutions	The structure of critical institutions, including the allocation of decision-making authority
Human capital	The skills, education, experiences, and general abilities of individuals
Social capital	The informal social networks and collective life of a community, as it influences the ability and willingness of residents to work together for common community goals
Risk management	The ability of a system to manage risks, including sharing the risk among the stakeholders
Information management	The ability of decision makers to manage information, including the processes by which information is acquired and assessed

Table developed by Reid, S., B. Smit, W. Caldwell, and S. Belliveau, 2007: Vulnerability and adaptation to climate risks in Ontario agriculture. *Mitig. Adapt. Strat. Global Change*, **12**, 609–637 from Yohe, G., R. S. J. Tol, 2001. Indicators for social and economic coping capacity–moving toward a working definition of adaptive capacity. *Glob. Environ. Change*, **12,** 25–40 and Smit , B., and O. Pilifosova, 2001: Adaptation to climate change in the context of sustainable development and equity. In: IPCC Working Group II (Ed.), *Climate Change 2001: Impacts, Adaptation and Vulnerability*. Earth Scan, Geneva).

both spatially and temporally, by livelihood system and socioeconomic group (Liverman 1999; Vásquez-León 2002).

Regarding adaptation, how farmers have responded to climate variability in the past has often informed our understanding of how they might respond in the future. For example, based on past response, Agrawal (2008) has suggested a typology of five categories of adaptation strategies to climate stress among poor farmers: diversification, mobility (e.g., migration), storage, communal pooling, and exchange. Among resource-richer farmers, other options to manage risk include buying farm insurance and proactive planning using decision support tools such as SCFs. Table 1 describes common determinants of adaptive capacity.

This chapter specifically reviews the role of SCFs as a determinant of adaptive capacity and examines the different research methods the empirical social science literature has employed in understanding the vulnerabilities and capacities of farming households and the potential role for climate information to modulate them.

2.13.3 Literature Review: Vulnerability, Adaptive Capacity, and Climate Information

The ability to forecast or project climate (short-term epochs, seasonal, and long term) and plan ahead has often been assumed to be critical to decreasing farming systems' vulnerability. The rationale is that if farmers know about the potential negative impact of the meteorologic events ahead of time, they can protect their crops (e.g., from frost and floods), apply climate-resistant technology (e.g., plant drought-resistant varieties or crops or use irrigation), pool risk (e.g., through diversification or storage), or buy insurance that would allow them to recover and start over. All these actions in principle increase their adaptive capacity; that is, their ability to prevent, cope, and recover from climate-related negative impact. Not surprisingly, through history, farmers have consistently devised different ways to predict climatic patterns to prevent and respond to their negative effects. However, the challenge of predicting climate is well documented and different approaches, from folk forecasts to scientific modeling, carry substantial levels of uncertainty that modulate their usefulness to farmers and other decision makers (e.g., see Lemos and Rood 2010). Although there has been significant investment in understanding the usability of climate forecasts around the world, relatively little is known about how climate information has affected the overall vulnerability of farmers. Rather than assessing outcomes of forecast use, most of the research so far has focused on understanding whether and why farmers use climate information or not.

For the past 30 years, one particular kind of climate prediction, seasonal climate forecasting has been the subject of significant research, especially in the social sciences, to understand the opportunities and constraints of using emerging technology to forecast climate up to a year in advance. Part of the motivation for this research has been to assess the value of forecasts as a decision-support tool. For example, while researching farmers in Florida, Cabrera et al. (2007) sought to estimate the value of climate information in reducing farm risk by helping farmers decide on management strategies that could both reduce negative impacts of climatic shifts, but also know when to take advantage of changes in weather conditions that would be more favorable for growing than expected given past conditions. Another goal of empirical research has been to use evidence from SCF application as an analog to understand potential challenges to the use of other kinds of climate information, especially global climate projections.

2.13.3.1 Seasonal Climate Forecasts as a Decision Support Tool

Since becoming available in the 1990s, various studies have consistently extolled the potential value of seasonal climate forecasts (Zebiak and Cane 1987; Magalhães et al. 1988; Glantz 1996; Ropelewski and Lyon 2003; Harrison 2005) to decrease farming vulnerability. In the mid-1980s, scientists interested in climate dynamics discovered the mechanisms of the El Niño-Southern Oscillation (ENSO) phenomenon well enough to be able to predict the onset of its warm (El Niño) or cool (La Niña) phase several months to even a year in advance. The ENSO phenomenon and its teleconnections wreak havoc on many tropical and subtropical regions of the world, disrupting normal patterns of rainfall to cause severe droughts and catastrophic flooding. The possibilities raised by climate scientists and policy makers alike that such a devastating climate variability could be anticipated and planned for were very appealing, especially if the worst climate-related impacts on poor populations worldwide could be avoided (Broad et al. 2002).

Although scientists did have some spectacular breakthroughs in ENSO predictability in the past two decades, the reality on the ground soon tempered the initial expectations. On the one hand, some users have been able to benefit from this new information. For example, many Pacific Island nations respond to El Niño outlooks and avoid potential disasters from water shortages; similarly, agricultural producers in Australia and the United States have been better able to cope with swings in their commodity production associated with drought (Hammer et al. 2001; Hartmann et al. 2002; Pagano et al. 2002; Hogan et al. 2010). On the other hand, these uses have been mostly in more developed regions and within well-funded and resourced groups in society. However, even in more developed countries such as the United States, documented SCF use among farmers has been low. For example, coming from similar perspectives, Hu et al. (2006), and PytlikZillig et al. (2010) have argued that overall, farmers' attitudes toward SFC use have remained poor and actual use has not increased despite improvements in climate predictions. Moreover, US farmers report a low level of understanding concerning climate variability and attach higher importance to short-term weather impacts at local spatial scales. In less developed regions, more often than not, the poorest of the poor have not benefited from the development of SCFs and, in some instances, have actually been negatively affected by it. For example, in Peru fishing companies have used SFC as one input to lay off workers when facing the possibility of a weak season and in NE Brazil, rain fed farmers' access to selected seed has been conditioned to a favorable forecast by the government (for a more detailed description see Broad et al. 2002; Lemos 2003).

2.13.3.2 Usability of SCFs

In theory, SCFs have many applications including supporting agricultural planning, water management, and disaster preparedness and response. In assessing the value of SCFs for the past 15 years, a rich empirical literature focusing on different sectors in different parts of the developed and developing worlds has emerged both in the social and natural sciences (Zebiak and Cane 1987; Pagano et al. 2002; Johnston et al. 2004; Harrison 2005; Vogel and O'Brien 2006; Lemos and Dilling 2007; Meinke et al. 2008; Gilles and Valdivia 2009; Roncoli et al. 2009; Hu et al. 2006; PytlikZillig et al. 2010). Findings from this literature suggest that successful application of SCF tends to follow a systems approach in which the SCF is contextualized to the decision situation and embedded within an array of other information relevant for risk management (Lemos and Dilling 2007). However, in practice, climate information is often perceived as 'outside' of the experience and routine of decision makers. For example, in the United States, PytlikZillig et al. (2010) contend that a significant hurdle to forecast use by farmers is that information about climate forecasts and tools is typically available in situations other than their "day-to-day activities and actual experiences" (p. 1334). In other words, climate information and forecasts are typically presented out of context, and therefore less useful for agricultural adaptation than they could be.

Research also finds that institutional and organizational factors play a critical role in fostering or constraining the use of SCFs in different sectors. In the Pacific Northwest US, environmental regulation (e.g., Endangered Species Act) has critically constrained the ability of decision makers to apply SCFs because it limited the range of decisions that could be made to guarantee compliance (Callahan et al. 1999). In Florida, Cabrera et al. (2007) found that government farm programs may be limiting (or failing to encourage) farmers' use of climate information by restricting the types of crops farmers can grow, and by raising crop prices that encourage larger monoculture farms that are less adaptable to climate variability. In addition, programs that seek to stabilize farm income tend to reduce farmers' perceptions of risk and urgency to adapt to climatic shifts (Cabrera et al. 2007).

Another critical finding from this literature is that the value of SCFs is fundamentally dependent on different users' ability, capacity, and willingness to respond to SCFs. Even if potential users have access to information, they may be powerless or unwilling to respond effectively. This applies both for highly regulated, wealthy institutions and for those individuals and groups living on the margin of survival. Much has been written, for example, on the lack of institutional capacity to respond to improved scientific predictions of stream flow, seasonal weather patterns, and climate (Pulwarty and Redmond 1997; Rayner et al. 2005). In the United States, water managers constrained by the high levels of accountability of their decision environment, prefer to rely on their professional experience rather than on SCFs to guide their management decisions (O'Connor et al. 2005; Rayner et al. 2005). Just having better information available does not necessarily lead to an improved response. For example, in the United States, Hu et al. (2006) found that changes to external factors (such as the accuracy of forecasts) have not resulted in increased use of information and adaptation by farmers, and argue that the focus of research should shift to understanding 'internal' reasons for using or not using forecasts – social and psychological factors – from the farmers' perspective. Similarly, among poor farmers in Africa and Latin America, the general lack of alternatives both in terms of technology and access to financial and human resources act as a critical constraint to their ability to use SCFs. Lack of resources among the most climate-vulnerable rain-fed farmers also curbs their ability to respond to forecasts even if they have access to them (Hammer et al. 2001; Ingram et al. 2002; Lemos et al. 2002). Similarly, extreme adaptive strategies such as changing livestock species are often not considered because of the risk, cost, and time involved in making such significant changes (Coles and Scott 2009). Other factors, such as perception of climate change, membership in networks, belief that information use will lead to economic and environmental benefits, and cultural traits and contexts. Credibility of the information and those producing it also influence willingness to use climate information (Roncoli 2006, Hu et al. 2006; Crane et al. 2010, Marshall et al. 2011).

Significant effort has been put into projects to help potential beneficiaries of SCFs realize those benefits, in both wealthy and poor regions. Importantly, successes are usually associated with an infusion of additional resources that potential users of SCFs were lacking in the first place, along with the new technology of SCFs (Lemos and Dilling 2007). For the systems/contextualized approach to work, participants usually have to have not only financial resources to come to meetings and access to information through the media, but must also be within the 'radar' of organizers of workshops; that is, the selection of potential users is often connected to specific implementation projects rather than widespread dissemination. When resources are available, interaction between model developers and users has been found to be the most critical factor driving usability. For example, in-depth studies of climate information use among water managers in the United States show that interaction between producers and users fundamentally influences the willingness of decision makers to apply climate information to their decision-making process (Engle 2010; Kirchhoff 2010). In Arizona, decision makers reported higher interest in using climate information after being given the opportunity to interact with climate model developers in a controlled social experiment (White et al. 2010). In Burkina Faso, a long-term SCF application project reported significant increase in use among poor rain-fed farmers after repeated interaction between project members and farmers (Roncoli et al. 2009). In Nebraska, farmers were more motivated to use forecasts or decision support tools when they felt they contributed to it; that is, when they have a sense of 'ownership' of the information rather than passively receiving it (PytlikZillig et al. 2010).

Based on this rich empirical research, different studies have advanced a range of recommendations to increase climate information use, especially if the goal is to decrease farmers' vulnerability. First, they recommend that predictions should be integrated into broader decision contexts that should take into consideration not just the magnitude and dimension of exposure to climate impacts, but also the sensitivities related to livelihoods, institutions, politics, cultures, and economic situation of potential users (Johnston et al. 2004; Klopper et al. 2006; Meinke et al. 2008; Roncoli et al. 2009). Thus, rather than providing forecasts as a 'fix,' governments should be supporting farmers to adapt sustainably (Hogan et al. 2010). Second, they suggest that proactive strategies rather than reactive ones should be encouraged. In Florida, Cabrera et al. suggest that seasonal climate forecasts would be most useful when they provide farmers with 'offensive' strategies that allow them to capitalize on favorable conditions, and for farmers who are more risk averse. In contrast, crop insurance and/or commodity loans while alleviating risk, make climate information seem less valuable to farmers. Third, communication, availability, perception of accuracy, training and credibility needs to be improved; for example, by targeting groups who have the most influence of farmers' choice (Hu et al. 2006; Crane et al. 2010; Artikov et al. 2006).

2.13.4 Assessing Vulnerabilities and Adaptive Capacities

As described, many studies have argued that understanding what motivates and limits the use of SCFs is not simple and involves accessing underlying social and psychological factors (Artikov et al. 2006; Hu et al. 2006; Marshall et al. 2011). To that end, a variety of social science methods have been used to try to understand farming systems' adaptive capacity and perceived vulnerabilities to climate change. In recent years, many vulnerability studies have covered a wide spectrum of risks and hazards while stimulating a rich debate about the many conceptual approaches to vulnerability and the methods to assess and measure it. Several factors contribute to the lack of consistency in the literature, including the multitude of disciplines and communities involved, the different contexts, scales, and areas of analysis, and diverging sources of methodology (Bohle 2001 cited by Kasperson and Kasperson 2001). One issue of particular debate is the dichotomy between top-down/ground-up strategies of vulnerability analysis. Although top-down approaches predominate in the literature, increasingly studies agree that there is a need to combine global/national level data with ethnographic and household survey approaches from the ground. For example, in their evaluation of vulnerability assessment methods for food security, Stephen and Downing (2001, p. 115) point out that socioeconomic indicators only contribute to one part of an entire information system. Hence, currently predominant assessments models look at climate hazard as one among many other stressors that shape farming households' vulnerability. This chapter reviews the most commonly used research methods to assess farmers' vulnerability, paying special attention to the strengths and weaknesses of these approaches.

An important consideration in conducting research about agricultural vulnerability and adaptive capacity is research design. The selected research design drives decisions about appropriate methods to use to collect information (Prokopy 2011). The choice of research design should be driven by theory and the research questions one is trying to answer. Research designs can include cross-sectional (one point in time) and longitudinal data collection. They can include experimental designs and case studies. One of the considerations in research design is 'unit of analysis'; that is, who is the subject of the study.

2.13.4.1 Who Is the Subject of the Study?

Despite the fact that many actors make decisions that influence farming systems' vulnerability and adaptive capacity, most research on this topic focuses on the farmer or the farming household as the unit of analysis. Figure 1 illustrates the many different scales of decision making and factors that influence the choice of farming practices (crop variety, fertilization choices, planting time, access to technology, etc.). Although the landowner and/or operator usually make the majority of farming decisions, they are influenced by both family members and advisors (e.g., extension agents, crop consultants) (Coles and Scott 2009; Hu et al. 2006). In turn, people making and influencing decisions are informed by the larger policy environment and past experiences, including past climatic conditions. The decisions themselves are shaped by farm characteristics such as farm size, soil quality, access to water, and so on. In any study to assess vulnerabilities and adaptive capacity, the starting point is to determine *who* to study.

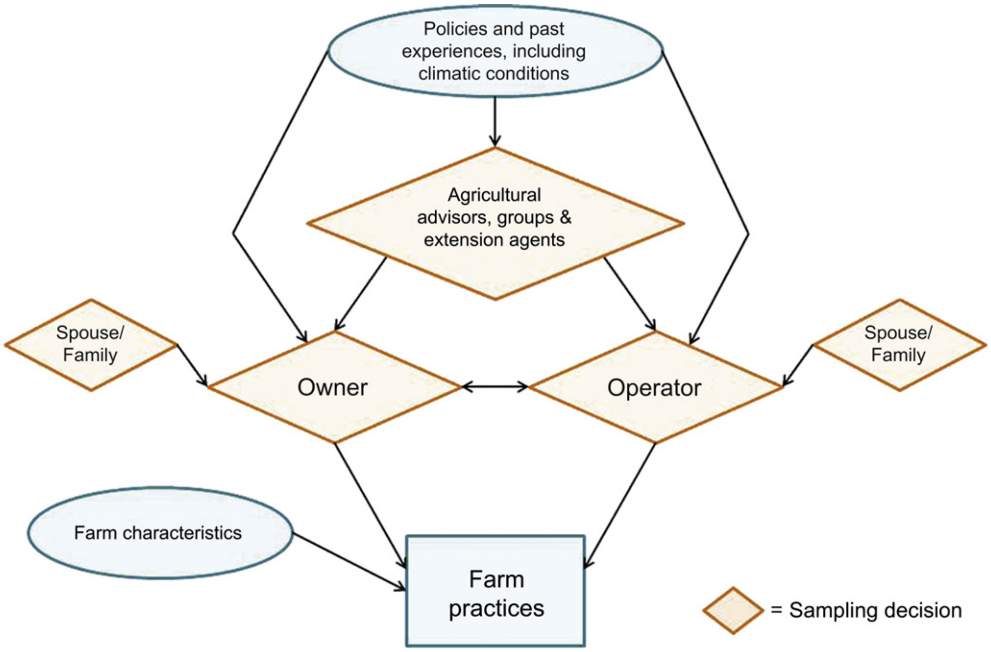
Policies and past experiences, including climatic conditions
Agricultural advisors, groups & extension agents
Spouse/ Family
Owner
Operator
Spouse/ Family
Farm characteristics
Farm practices
= Sampling decision

Figure 1 Different scales of decision making and factors that influence choice of farming practices.

2.13.4.2 Acquiring a Sampling Frame

A sampling frame is a complete list of all people meeting the criteria determined by the study. For studies in which generalizability to a complete population is the goal, a random sample or census of this population will usually be assessed. For studies in which in-depth understanding is desired, developing a random sampling frame is less important and results from nonrandom sampling approaches (e.g., snowballing, purposive sampling – in which subjects are chosen because of some desirable characteristic) are likely to be less generalizable to other contexts.

Finding a sampling frame for conventional farmers in developed countries can be relatively straightforward. For example, Smit et al. (1996) were able to access a list of all farmers in three townships in southwestern Ontario through municipal office records for their quantitative farmer climatic variation adaptation survey. However, finding a sampling frame for nontraditional farmers may be more difficult. Smaller and more diverse farms are less likely to participate in government programs (Nickerson and Hand 2009). Also, because of barriers to certified organic adoption (Constance and Choi 2010), many farms that are essentially organic are not certified. One solution in the United States is to access publically available county landowner records. By surveying all landowners with more than five acres in a particular geographic location, one captures the majority of the nontraditional farming study population. However, this strategy introduces elements who are not part of the study population (nonagricultural landowners). Although these data can be discarded, this method may result in a substantial waste of money and time.

2.13.4.3 Probability Sampling

For quantitative research to be generalizable to a larger population, a probability sampling method must be used. The most basic probability sampling method is simple random sampling, in which the people to be studied are selected from the complete sampling frame only by chance. Generally, this method involves using a computer program to assign each case a number and then generate a random selection of the appropriate sample size.

One problem with simple random sampling is that certain strata in a population might not be well represented in the sample. For example, to compare farmers in the United States based on ethnicity, a simple random sample of farmers is not likely to result in an adequate number of minority farmers for comparisons to be made. In this case, disproportionate stratified sampling is needed. In other words, the sampling frame is divided on the basis of a particular stratum, which in this case is ethnicity. Then, each section of the sampling frame is sampled randomly, but not in proportion to the representation of each stratum (i.e., ethnicity) in the population. That is, a higher proportion of the less common strata will be selected than by simple random selection, so that each stratum is well represented in the sample.

2.13.4.4 Nonprobability Sampling

Although quantitative methods require large randomly selected samples, qualitative methods are more appropriate for small samples that are selected purposefully (Patton 2002). Magistro and Roncoli (2001) suggest that "a more localized, detailed understanding of a given geographical setting reflects the complexity of real life decisions and situations" regarding human adaptation to climate (p. 92).

There are many strategies for selecting a sample in qualitative research. Key informants, or people who are knowledgeable or important in the community, and who are willing to cooperate with researchers, are often excellent subjects to interview. In situations in which the researcher does not know how to reach the appropriate sample or does not have enough cases in the sample, snowball sampling may be advantageous. In snowball sampling, the researcher asks each respondent to recommend other potential respondents (Patton 2002). Snowball sampling can, however, result in sampling bias. For example, Coles and Scott (2009) found that 'snowballing' to augment their sample of southeastern Arizona farmers and ranchers may have "resulted in a set of respondents that are more connected and informed than in general" (p. 300). In this case, some variability that would have been present with a more random sample is desired.

2.13.5 Methods

In general, the purpose of a study drives the choice of the appropriate social science method(s). If the purpose of the study is actually to change behavior, then participatory research may be most appropriate (Roncoli 2006), although other methods often have behavior change as a goal. Many studies will use a mixed-methods approach (use of more than one method, such as interviews followed by a survey) to develop a more comprehensive understanding of the issue.

2.13.5.1 Surveys

Surveys generally consist of a questionnaire administered through the mail, over the phone, on the Internet, or in person. The mode(s) used depend on characteristics of the target population, the information (addresses, phone numbers, e-mails, etc.) contained in the sampling frame, and the resources (money, staff, time, etc.) available to the researcher. At times, multiple modes are used for administering questionnaires to increase the response rate and therefore decrease response bias. As response rates increase, a wider diversity of people and opinions are surveyed, which makes the results more generalizable to the entire population (assuming a probability sampling approach was used). Questionnaires can consist of close-ended questions, in which people can check boxes that apply to them, or open-ended questions, in which they write out responses, or a combination of both. Considerations for developing and choosing questions include the research questions and relevant variables, the survey mode, past research and theory, and the respondents' ability and willingness to answer. Careful question development and survey formatting is important not only to response rate, but also to validity. (Are the data an accurate reflection of reality?) For a comprehensive guide to developing and administering surveys, see Dillman et al. (2009).

Many of the studies reviewed in this chapter used surveys to collect their data in the context of different theoretical and analytical approaches (Lemos et al. 2002; Hu et al. 2006; Mertz et al. 2009). Because Lemos et al. (2002) wanted to understand how different farming households used climate information to decrease their vulnerability to drought, they stratified their random sample by different geoclimatic regions in northeast Brazil. That allowed the research team to better assess how other factors beyond climatic and geographical factors (exposure) affected SCF use. Mertz et al. (2009) used a household survey to provide "the basis for a quantitative characterization of household perceptions of CCV [Climate Change and Variability], adaptation to CCV and changes in household resource management and livelihood strategies over the past 20 years" in the savanna zone of central Senegal (p. 808). In the context of these rural Senegalese villages, it was necessary for researchers to administer surveys in person. Using a mixed-methods approach, Mertz et al. (2009) also carried out informal interviews with key informants and focus groups to complement the quantitative analysis.

2.13.5.2 Interviews

One commonly adopted method to acquire more detailed and rich data in mixed methods approaches (i.e., quantitative and qualitative) are in-depth interviews. These interviews are often used in exploratory research when the relevant variables are not well defined. They are also indicated in research in which variables are not easily quantifiable and in-depth description of factors explaining outcomes are necessary. For example, if a research goal is to understand how different past experiences influence farmer's willingness to use climate information, in-depth interviewing may be a good method. The same applies for information that may require a certain level of trust between informant and interviewer. In social science research, an interview generally involves a researcher asking an interviewee open-ended questions, a format that allows the respondent to provide content and meaning to the conversation. The conversation is recorded and then transcribed or the interviewer takes notes during or after the interaction. In our examples, different approaches to qualitative interviewing have been used. For example, because note- taking can be unreliable and not always consistent, the research teams collecting data in Crane et al. (2010) chose to record and transcribe their interviews with farmers in Georgia, the United States. However, other researchers have chosen to take detailed field notes during the interviews (Coles and Scott 2009). Still other teams, such as Cabrera et al. (2006) have a group of people participate in each of their interviews and then afterward have team members compare and discuss their notes to check for consistency. Interviews can also be conducted over the phone. Format and length of interviews also vary. In their study of farmers' skill in using climate forecasts, Crane et al. (2010) used 'semistructured' interviews, which was essentially a hybridized conversational/interview guide approach. Rather than follow a structured interview guide, interviewers loosely followed a predetermined interview protocol, which "was designed to elicit information on farmers' production systems, climate-sensitive management decisions, use of weather and climate information systems, and potential application of seasonal climate forecasts" (p. 47). However, the researchers wanted interviewees to at least partly guide the conversation, allowing for a conversational flow and new perspectives and insights. Overall, with each study population, the object is to conduct as many interviews as needed to reach data saturation, or the point at which no new patterns or themes emerge from subsequent interviews.

Interview guides are also useful when moderating focus groups, a type of small group interview. Focus groups are generally conducted with groups of 6–10 people from similar backgrounds, and several focus groups are usually conducted to ensure breadth in the data. The purpose of conducting focus groups is to collect responses from people in a social context in which respondents hear the reactions of others (Patton 2002). Focus groups are often used in concert with other methods either in the exploratory phase of research or as a way to supplement other data. As previously mentioned, Hu et al. (2006) conducted focus groups with Nebraska farmers in the exploratory stage of their research to identify and define key variables that should be used later in the survey. In their study of farmer climate change adaptation in Sahel, Mertz et al. (2009) used focus group data not only to develop the list of important concepts, but also to triangulate with data from key informant interviews and household surveys.

Although focus groups offer efficiency in that numerous individuals are interviewed at one time and can be effective at getting high-quality data, there are a number of limitations. First, shy individuals or those with minority viewpoints may not have the opportunity to express their perspectives. Second, focus groups require a skilled moderator who can manage groups of people and effectively guide the conversation. Third, because confidentiality and anonymity are not assured, respondents might feel uncomfortable expressing embarrassing or controversial opinions. Therefore, focus groups are at times not an appropriate method for controversial topics (Patton 2002).

2.13.5.3 Mental Models Interviews

Mental models interviews are a type of interview that can be used to assess farmers' perceptions of their vulnerability and adaptive capacity to climate shifts. The rationale for using mental models as an approach is the belief that the experiences people use to inform their decisions regarding complex issues are organized in a mental framework (or mental model) of associated or related concepts (Morgan et al. 2002). Mental models interviews are designed to capture current beliefs (correct and incorrect) without creating beliefs through the wording of questions, with the goal of visually displaying respondents' mental models. These visualizations, also called concept maps, allow comparisons to be made between groups, including the public and experts (Morgan et al. 2002; Bostrom et al. 1992; Lazo et al. 1999).

Mental models interviews, often used to understand risk perceptions, are typically semistructured interviews that begin with broad questions about the general topic of interest, to allow the interviewee to direct the flow of the conversation and express their views without the researcher imposing ideas or terms on the respondent (Morgan et al. 2002). A standardized interview guide should be developed and pretested with representative farmers and experts to ensure consistency across the interviews (Morgan et al. 2002). If the focus of the interviews is to identify gaps in the knowledge of farmers as compared to risk 'experts,' a mental model of agricultural vulnerability to climate variability could be constructed first, from interviews with these experts. Next, interviews would be conducted with farmers, and mental frameworks developed based on the expert model of vulnerability and adaptation to climate variability. This particular methodology does presume that experts have a more complete mental framework of the risks to agriculture from climate than do farmers.

Mental models interviews with farmers and experts about this topic might initiate with a question like, "Tell me what you think about the effects of climate variability on your farm" or even more broadly, "Tell me what you think about the effects of climate variability on U.S. agriculture." When there are particular areas of interest to the researchers, such as perceived vulnerability or adaptive capacity, specific prompts are included later in the interview guide so they can be addressed after the interviewee has had a chance to describe all of his or her initial thoughts about the broader topic.

The mental models diagrams constructed from these interviews highlights the similarities and differences between the vulnerability and adaptation frameworks of farmers and climate experts. Areas of consensus and divergence uncovered by the interviews could be used to inform policies and improve communication between climate vulnerability and adaptation experts and the farmers they are trying to persuade.

2.13.5.4 Participatory Approaches

Participatory approaches include numerous methods that involve research participants collaboratively in the research. Participatory approaches can be especially useful when the project goal is to achieve behavioral change or increase the usefulness of climate knowledge.

One participatory approach employed by Cabrera et al. (2008) is to involve participants in the development of models. In an iterative process involving scientists, farmers, consultants, and other stakeholders, the team of researchers created the Dynamic North Florida Dairy Farm model (DyNoFlo), a model used to help farmers make management decisions with the goal of reducing nitrogen runoff while promoting profitability. Their methods included exploratory interviews, site visits, focus groups, a *sondeo* or rapid rural survey (Hildebrand 1981), and farmer trials of a prototype model. Because stakeholders were involved throughout the process of model development, the resulting DyNoFlo model was usable and useful to farmers.

In another good example of how interaction between researchers and producers can increase understanding and accessibility, Ziervogel (2004) used a role-playing game to investigate how smallholder farmers in the African country of Lesotho would likely use seasonal forecasts in farm and household decision making. The role-playing game was conducted with small groups. First, participants collaboratively drew maps of their village. Then, three rounds, each representing 1 year, were commenced with a mock radio address announcing that season's forecast. During each round, participants were asked to look at the map and describe the farming and household decisions they would make based on the given forecast. Although the resulting data were hypothetical, there are a few advantages to using a role-playing game in lieu of a survey. Namely, the speculative decision making is given more contextual realism in that participants are interacting and communicating with others, responding to the mock forecast, and using a map to think about resources (Ziervogel 2004).

It would be futile to study farmer vulnerability and adaptation to climate variability without considering the benefits of the research to the farmers. According to Roncoli (2006), the aim of participatory research is to create change in the study community. Although qualitative and participatory studies do not lend themselves to generalizability and replication, they often result in participant learning and empowerment.

2.13.6 Case Study: Understanding Vulnerability and Adaptive Capacity to Enhance Usability of Climate Information in the North Central Region of the United States

The goal of the Useful to Usable (U2U) project is to improve the resilience and profitability of grain farms in the north central region of the United States amid variable climate through the development and dissemination of decision support tools, resource materials, and training. The U2U project consists of a diverse group of state climatologists, crop modelers, agronomists, economists, and social scientists who are working collaboratively to develop decision support tools that are usable by farmers and their advisors and that meet their needs. Building on the findings of the studies reviewed in this chapter, the U2U project is collecting information from potential users that will help to develop tools that will actually be used to improve adaptive capacity and reduce vulnerabilities.

Because the study area is too large to conduct in-depth participatory research, team members are initially surveying farmers throughout most of the region. However, the working hypothesis is that farmers may not ultimately be the ones using climate information in decision making and so there is a strong emphasis on finding out the needs of advisors – including extension agents, crop consultants, bankers, employees of the US Department of Agriculture, agricultural retailers, and others. Surveys of advisors are being conducted in four key states in the region. Both the producer and advisor surveys seek to find out when in the calendar year key farming decisions are made, whether people already use climate information in their planning, and what are current levels of adaptive capacity. To further understand how decisions get made and who influences producers, a stakeholder network analysis will also be conducted in these four states.

After gathering and analyzing the survey data, climate model developers and social scientists will work together to develop decision support tools that meet the expressed needs and interests of end users. High resolution, gridded crop models will be developed for the region and the impact of climate and management decisions on crop yield and farm profitability will be determined for four representative farm types. Based on the calendar information that emerges from the surveys, the goal of the modeling will be to provide information to people at critical times of the year to help with both short- and long-term farm planning decisions. Outreach and training materials will be targeted at appropriate audiences (producers, advisors, or both) based on the outcomes of the network analysis. Recognizing that a participatory approach is ideal for developing tools that can actually change behaviors and increase adaptive capacity, the team will work interactively with producers and advisors to evaluate and adapt these tools and outreach materials in an iterative process of co-production in four states. In-depth interviews and focus groups will be used throughout this iterative process. Only after the tools are clearly meeting needs in the four-state region will dissemination be extended across the entire 12-state region. This ambitious project is funded primarily by the USDA's National Institute of Food and Agriculture started in early 2011. More information can be found at www.agclimate4u.org.

2.13.7 Conclusion

Gaining a better understanding of farmers' vulnerabilities and adaptive capacities is essential for developing climate information that they can and will use to adapt. The literature review presented in this chapter illustrated that it is not always straightforward for farmers to use climate information. Only by better understanding gaps in adaptive capacity can these gaps be addressed. To that end, key social science methods such as the ones presented in this chapter can be used to identify and understand current levels of adaptive capacity. With this knowledge, the promise of collaboration with climate model developers to prepare climate forecasts and information in ways that farmers can use to improve their adaptive capacity can be fulfilled.

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2.14 Vulnerability of Indian Agriculture to Climate Change

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Glossary

Kharif crops Crops that are grown during the rainy season are 'Kharif' crops. Kharif crops are usually sown with the beginning of the first rains in July, during the south-west monsoon season.

Rabi crops The term is used in the Indian subcontinent for agricultural crops which are sown in autumn and harvested in the winter season. Crops that are grown during the winter season are called as 'Rabi' crops.

Dhencha 'Dhencha' is a local name for 'twigs of Sesbania.' The plant thrives on waterlogged soil and is grown in areas under reservoir submergence areas. It increases the total nitrogen, organic matter content of the soil in which it is planted, thus increasing the yield of the subsequent crop. It is also extensively used as a green manure for fish cultivation in India.

PRECIS PRECIS is a regional climate modeling system used to generate high-resolution climate scenarios at a regional scale. It is useful to identify how a country or a region can best adapt to the climate change–related impacts.

Taag Taag is a local name for sun hemp. It grows very fast and provides nutrients to the soil. Like Dhencha, it is also used as a green manure crop.

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2.14.1 Introduction

Agriculture is closely linked to climate. Crops require optimal temperatures and moisture levels for their full growth. Changes in temperatures, precipitation, and seasonal variations will have adverse impact on the food crops and decrease their productivity. With the increasing pressure of meeting the demands of growing population, climate change is expected to bring new challenges for India's agriculture sector.

Agriculture is the primary occupation in rural India and a source of livelihood for two-thirds of the country's population. The sector therefore, remains an important component of the poverty strategies such as Millennium Development Goals (MDGs). The vulnerabilities in agriculture are not just limited to production losses, but have a major socioeconomic impact. This chapter discusses the existing vulnerabilities and risks that the agriculture sector in India is facing and assesses the potential risks due to climate change. The study concludes that adaptation to climate change should also act as a measure for bringing livelihood reforms and reduction of poverty. Building on traditional practices and local technological innovations will help in rooting the interventions and upscale them.

The chapter is presented in six sections. Section 2.14.1 provides an introductions and setting of the context. Section 2.14.2 outlines the profile of agriculture sector in India with recent trends and characteristics of various agroclimatic zones. This section also outlines key issues in agriculture in the country. Section 2.14.3 presents an assessment of existing vulnerabilities and associated risks. Assessment of projected impacts on production patterns of major crops along with cross-sectoral and other associated impacts is presented in Section 2.14.4. Section 2.14.5 discusses various strategic interventions to respond to climate change. Key learnings from the research are presented as concluding remarks in Section 2.14.6.

2.14.2 Profile of Agriculture Sector in India

Agriculture contributes to about 30% of the national income and 8.56% of the country's exports which include rice, cashew nuts, tea, horticulture, and floriculture products (GoI 2006). About 58% of India's population depends on agriculture for their subsistence. Considering the fact that out of 1210 million of India's population, 833 million (i.e., 68.84%) reside in rural areas, agriculture has a major role to play in enhancing the rural economy (Census 2011).

The share of agriculture in the country's Gross Domestic Product (GDP) is 14.2%. However, in the recent years this share is seen to decline. The main reasons behind this decline are the rapid growth of population and the growth of industrial and service sector economy (GoI 2011). In the near future, producing enough food for meeting the increasing consumption demands of the growing population is going to be a major challenge for the country. **Figure 1** shows that out of the total area of 140.86 million hectares (MH) under cultivation only 62.29 MH land is under irrigation whereas the remaining 78.57 MH (about 56%) is rain fed. This statistics indicates high vulnerability to climate change.

2.14.2.1 Major Agroclimatic Zones in India

Agriculture in India is heavily dependent upon the monsoons. The south-west monsoonal winds are the main source of rainfall to the country. Although some rainfall is also brought by the south-east winds, the proportion is far less. The amount and distribution of rainfall during the monsoon period are the key determinants for the production of food grains. The summer monsoon (Jun.–Sep.) contributes 78% of India's annual rainfall and is a major source of water (GoI 2004).

As a part of the Seventh Five Year plan (1985–90), the Planning Commission of India, divided the country into 15 broad agroclimatic zones. The zones were delineated on the basis of climate, physiography, resource development and utilization, and resource constraints and potentials (Planning Commission 1989). **Figure 2** indicates the list of zones identified on this basis. There is a large variation in the climate, topography, and soil conditions across the agroclimatic zones.

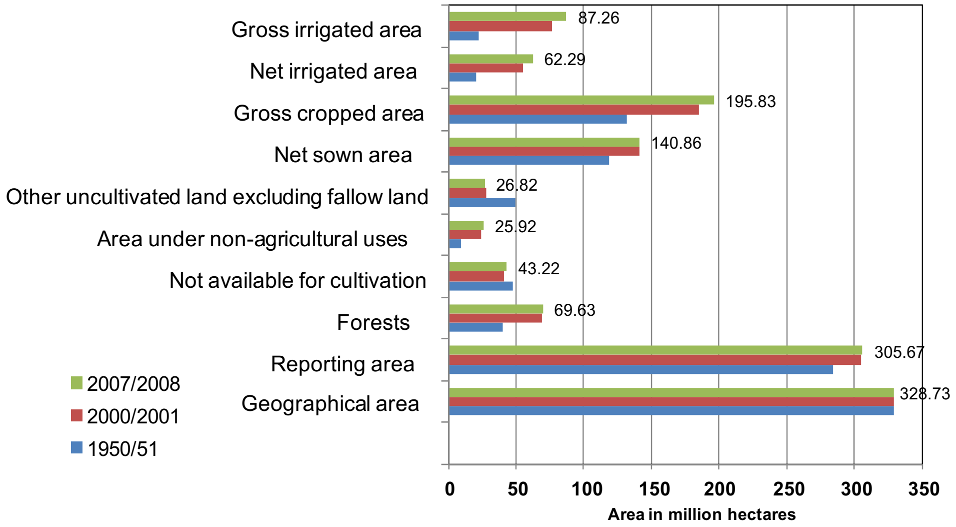


Figure 1 Distribution of land use in India from 1951 to 2008. Data source: Government of India (GoI), 2008: Directorate of Economics and Statistics, Department of Agriculture and Cooperation, Ministry of Agriculture, GoI, New Delhi. [Available online at http://eands.dacnet.nic.in/Advance_Estimate-2010.htm.]

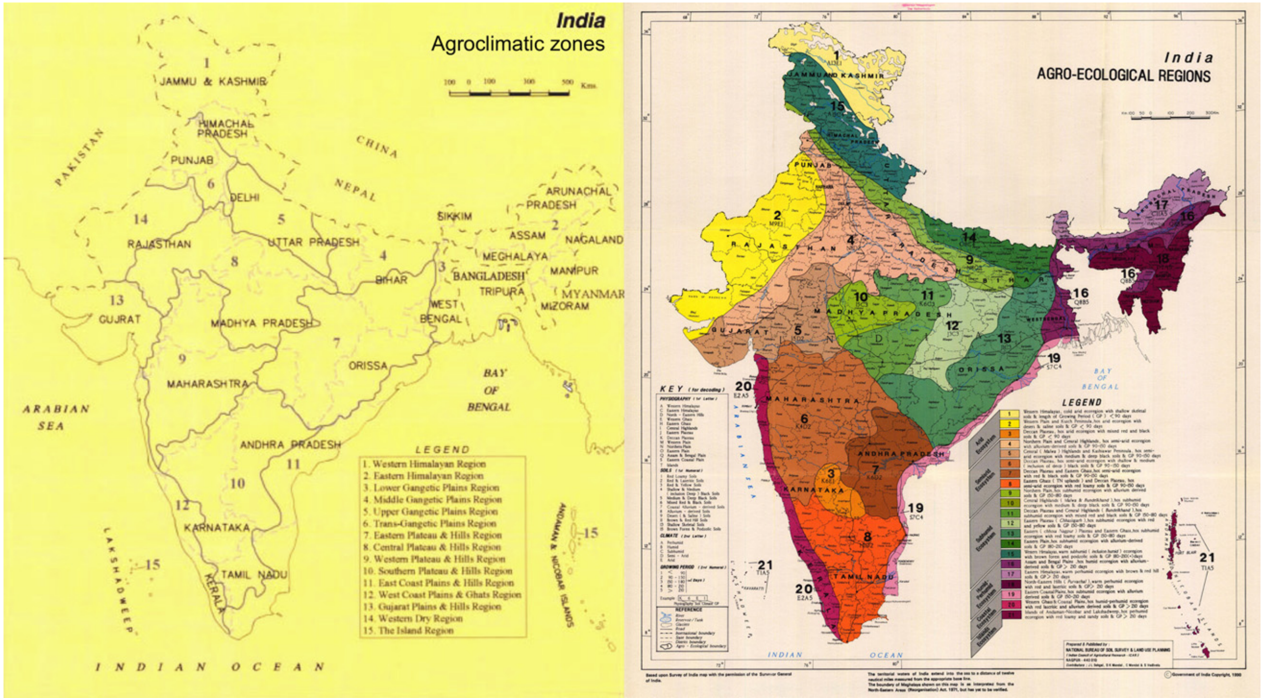

India
Agroclimatic zones
JAMMU & KASHMIR
HIMACHAL PRADESH
PUNJAB
DELHI
RAJASTHAN
UTTAR PRADESH
GUJRAT
MADHYA PRADESH
MAHARASHTRA
ORISSA
ANDHRA PRADESH
KARNATAKA
TAMIL NADU
KERALA
BIHAR
WEST BENGAL
SIKKIM
ASSAM
ARUNACHAL PRADESH
NAGALAND
MEGHALAYA
MANIPUR
TRIPURA
MIZORAM
BANGLADESH
MYANMAR
CHINA
NEPAL
PAKISTAN
ARABIAN SEA
BAY OF BENGAL
INDIAN OCEAN
LAKSHADWEEP
ANDAMAN & NICOBAR ISLANDS
LEGEND
1. Western Himalayan Region
2. Eastern Himalayan Region
3. Lower Gangetic Plains Region
4. Middle Gangetic Plains Region
5. Upper Gangetic Plains Region
6. Trans-Gangetic Plains Region
7. Eastern Plateau & Hills Region
8. Central Plateau & Hills Region
9. Western Plateau & Hills Region
10. Southern Plateau & Hills Region
11. East Coast Plains & Hills Region
12. West Coast Plains & Ghats Region
13. Gujarat Plains & Hills Region
14. Western Dry Region
15. The Island Region
India
AGRO-ECOLOGICAL REGIONS
LEGEND
KEY (for decoding)
INDIAN OCEAN
BAY OF BENGAL
ARABIAN SEA

Figure 2 Agroclimatic zones and agroecological regions defined by the Planning Commission of India. Source: Planning Commission, 1989: *Agroclimate Regional Planning: An Overview*. Government of India, New Delhi.

This has led to wide distribution in the type of crops, yield, varieties grown, and farming practices across the zones.

2.14.2.2 Trends in Agriculture

In terms of geographical spread, about 43% of country's land is used for agriculture purposes. However, huge population size creates a gap in the demand and supply of food grains. India holds only **2.3% share in the total land area of the world while it hosts about 17.5% of the world's population** (second largest in the world). It is estimated that the requirement of food stock to feed India's projected population of 1.4×10^9 in 2030 will be 114 million tons of rice, 83 million tons of wheat, 13 million tons of maize, 106 million tones of fruits and 193 million tones of vegetables (TERI 2005 as cited by Kelkar, 41 pp.). **Considering the situation of land availability and irrigation, maintaining the food security is going to be a major challenge.**

To cater to the increasing demand of food supplies, the Department of Agriculture (DoA) has taken steps to increase the percentage area of land under cultivation. The Green Revolution program initiated in 1967, focused on increasing the country's food production. The overall production of the country increased during this time. The key reasons attributing to this increase were expansion of agricultural land, development of high yielding and drought proof varieties, increased use of fertilizers and biocides, and improved irrigation systems. Under the Green Revolution, an additional 22.48 MH of land was brought under agriculture and 36.49 MH under irrigation. The food production increased from 50 million tons in 1951 to 212 million tons in 2012. During this time, the mean cereal productivity also increased from 500 to 1800 $\mathrm{kg\,ha^{-1}}$ (GoI 2004).

Although the Green Revolution has contributed to a significant rise in the food production, the production was confined to irrigated areas only. Further, excessive use of chemical fertilizers, pesticides, and genetically modified seeds reduced the fertility and crop production capacity of the soil. The long-term impacts of these interventions were found to be adverse or negative.

Further, only 25% of the farmers produce 60% of the country's total agricultural output (TERI 2005 as citied by Kelkar 2006 40 pp.). As per the 'All India Report on Agriculture Census 2005–06' (GoI 2012), the numbers of operational landholdings in 2005–06 have increased from 120 million (2000–01) to 129 million (2005–06). However, about 83.29% of these are small and marginal holdings (i.e., below 2 ha) and only 15.86 and 0.85% are semi-medium and large holdings, respectively.

Most of the irrigated lands are owned by large farmers who constitute to a very small proportion of the farming community. **India's agriculture is thus characterized by small landholdings with majority of the farmers practicing subsistence agriculture.** These farmers do not have a direct access to the markets. A large share of their farm profits is taken by people who act as middle man/intermediaries for selling the agricultural produce in the markets. Since the economic condition of these farmers is poor, they are not able to afford the cost of adopting new technologies and irrigation. Further, since rain-fed varieties grow only once in a year, the agricultural production is limited only to half the capacity.

2.14.2.3 Government's Initiatives in Agriculture

Government of India (GoI) has taken various policy-based initiatives for improving the socioeconomic condition of poor farmers. Welfare schemes related to health, education, banking, infrastructure support, markets, transport, etc., have been made. These policies and schemes have made some contribution to alleviate the situation of poverty and improve the condition of agriculture; however, these initiatives were isolated (without strong interconnections/linkages) and hence did not receive much success.

The policies and schemes implemented so far focused on increasing the production levels and subsidizing the costs for small and marginal farmers. This has led to rapid production of food grains resulting in degradation of land. Unfortunately, the subsidies provided increased the dependency of the poor farmers.

To make agriculture sustainable and a profit-making enterprise, a transformation in policy and decision making is required. The policies and programs should focus on developing the capacity of the small and marginal farmers. **While doing so, a shift from subsidy to investments is required. Efforts to improve the knowledge in agribusiness, improved management practices, input management, marketing, supply chain, information, etc., are necessary.** Certain forms of subsidies such as under pricing of water and zero/low pricing of electricity for pumping water may be still needed. However, rationalization of these subsidies with sectoral investments will be appropriate. The Eleventh Five Year Plan: 2007–12 prepared by Planning Commission (GoI 2008a) focuses on increasing sustained food production and shifting the subsidies to investment-based approach.

2.14.2.4 Key Issues

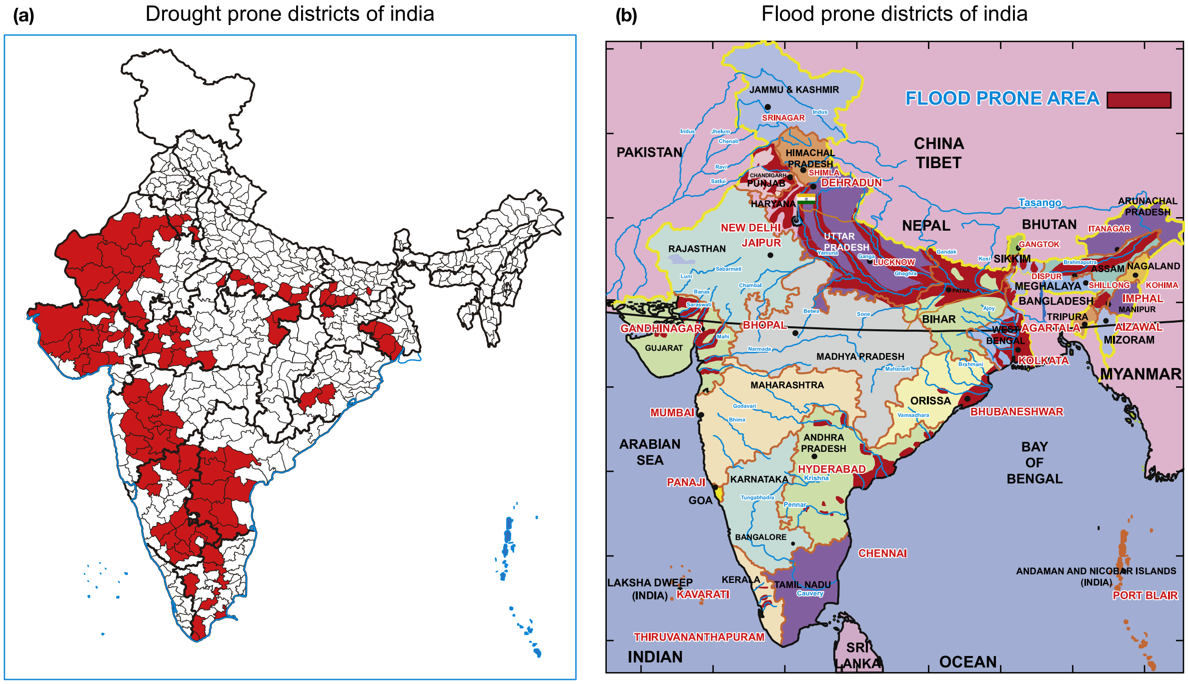
2.14.2.4.1 Increasing Frequency of Droughts and Floods

About one-third of the land in India is either drought or flood prone. Figure 3 (a) and 3(b) provides the geographical spread of the drought and flood prone districts in India respectively. In the past 50 years, the country has faced 15 major droughts and 7 severe floods (GoI 2004). The average rainfall of the country is 11, which is 39 mm higher than the annual global average; however, the regional variation in the pattern of rainfall is rather high. About 73% of the annual rainfall is received in less than 100 days; whereas 33% of the cropped area identified as chronically drought prone receives less than 750 mm annual rainfall. In these areas, even a rainfall of 400 mm would be adequate for the growth of crops, while in a high rainfall place such as Assam, a rainfall of even 1000 mm would not be sufficient and may create situations/conditions of droughts (GoI 2009) (**Figure 3**).

The National Flood Commission's (NFC) Report (1980) indicates that 40 MH of the land is prone to flooding. The flood zones are largely situated along the Indo-Gangetic plains, north-eastern states, and at some sections in the central river basins.

Between the periods of 1955–2004, the average crop area of 3.59 MH was affected due to the flooding. The crop area affected during 1988 was 10.15 MH. Another period when the flood impacts were severely felt was the period of 1976–78. A total of 4.105 MH of land came under flooding. The estimated crop damages were Rs. 786 millions (NFC 1980).

The assessment of the rainfall pattern shows that 68% of India is vulnerable to droughts. The drought areas extend over the western and peninsular regions of Rajasthan, Gujarat,


(a) Drought prone districts of india

(b) Flood prone districts of india

FLOOD PRONE AREA
JAMMU & KASHMIR
SRINAGAR
PAKISTAN
CHINA
TIBET
HIMACHAL PRADESH
SHIMLA
CHANDIGARH
PUNJAB
DEHRADUN
HARYANA
NEW DELHI
JAIPUR
RAJASTHAN
UTTAR PRADESH
LUCKNOW
NEPAL
BHUTAN
ARUNACHAL PRADESH
ITANAGAR
GANGTOK
SIKKIM
ASSAM
NAGALAND
DISPUR
MEGHALAYA
SHILLONG
KOHIMA
IMPHAL
MANIPUR
BANGLADESH
TRIPURA
AGARTALA
AIZAWAL
MIZORAM
BIHAR
WEST BENGAL
KOLKATA
MYANMAR
GANDHINAGAR
GUJARAT
BHOPAL
MADHYA PRADESH
MAHARASHTRA
ORISSA
BHUBANESHWAR
MUMBAI
ARABIAN SEA
ANDHRA PRADESH
HYDERABAD
BAY OF BENGAL
PANAJI
GOA
KARNATAKA
BANGALORE
CHENNAI
ANDAMAN AND NICOBAR ISLANDS (INDIA)
PORT BLAIR
LAKSHA DWEEP (INDIA)
KAVARATI
KERALA
TAMIL NADU
THIRUVANANTHAPURAM
INDIAN
OCEAN
SRI LANKA

Figure 3 Drought and flood prone areas in India. (a) Drought prone districts of India. Source: State of Environment Atlas, undated: *Environmentally Sensitive Zones, Drought Prone Districts in India*. New Delhi. [Available online at http://www.soeatlas.org/PDF_Map%20Gallery/Drought%20Prone%20Districts.pdf.]; (b) Flood prone districts of India. Central Water Commission, undated: Ministry of Water Resources, Government of India, New Delhi. [Available online at http://ndma.gov.in/ndma/guidelines/flood.pdf.]

Orissa, Maharashtra, Andhra Pradesh, Jammu & Kashmir, Himachal Pradesh, and Bihar (Mahapatra 2001). The year 1987 was one of the most severe drought years. During this year, the rainfall deficiency was 19%. About 59–60% of the crop area was affected and 285 million people were impacted. In the recent years, the drought of 2002 was the most severe. The rainfall deficiency during the monsoons was 51% (lowest in the history). The production of food grains declined to 29 million tones, whereas the estimated financial loss to agricultural income was Rs. 390 000 millions (Samra 2004 as cited in GoI 2009, 13 pp). The early season droughts, i.e., when rainfall deficiency is observed in the months of Jun.–Jul., provide sufficient time for the farmers to mitigate the adverse situations, as compared to the late season droughts where rainfall is scarce during the month of September.

Although rainfall variation is one of the key reasons for arising of drought and flood situation in India, other reasons such as depletion of forests, poor water management strategies, overexploitation of the ground and surface water resources, poor irrigation systems, inadequate infrastructure, etc., have lead to increasing the vulnerability.

Climate change is further expected to distort this cycle of droughts and floods. The rise in temperatures and increase in intensity of the rainy days will result in spatial and temporal variations in climate, thereby adversely impacting the cropping cycle and production levels.

2.14.2.4.2 Security of Food

The food security for India is already under threat with the recurrence of droughts and floods. The growing increase in population and distortion of drought and flood cycle would further induce an additional stress. If the population continues to grow at this rate, by 2020 the demand for key food crops such as rice, wheat, coarse grains, and cereals is estimated to rise substantially.

The estimated demand for food crops for 2020 against the production achieved in 2000 is estimated to grow by about 37 Mt for rice and 32 Mt for wheat. The demand for fruits and vegetables is estimated to grow by 36 and 65 Mt, respectively. The demand for milk and milk products is expected to grow by 67.5 Mt (GoI 2004 83 pp.). **Figure 4** provides a graphical representation of the production and demand of food crops in the country. Considering that the total area under agriculture will not increase, feeding the increasing population is going to be a real challenge for the country.

To meet the increasing demand, there is a need to develop an effective drought and flood management system, which could prevent/control the losses of food production. This would include developing early warning systems, flood control mechanisms, drought resistant varieties, and increasing the agricultural productivity in general.

2.14.2.4.3 Degradation of Land

The issue of land degradation is further contributing to the loss of production. The annual rate of growth in food production and yield peaked during the early years of the Green Revolution, but it has declined since the 1980s (GoI 2004 83 pp.). Some of the main reasons for this are use of harmful pesticides and fertilizers that affected the fertility levels of the soil after the initial harvests, indiscriminate extraction of groundwater leading to reduced water tables, and increased salinity of the soil. The mid-term assessment of the 11th Five Year Plan (GoI 2008a) suggests that the fertilizers used for enhancing the crop production has led to micronutrient deficiencies in the soil, leading to reduced capacity of crop growth and production. According to a study conducted by Ajai et al. (2009), out of the country's total geographical area of 328.73 million, 57% is either desertified or degraded. An optimum mix of fertilizer, along with sound crop management practices is required for reducing the issue of land degradation.

2.14.2.4.4 Increasing Poverty

Poor farmers practice subsistence agriculture and usually have a hand to mouth living. Their annual year's income is

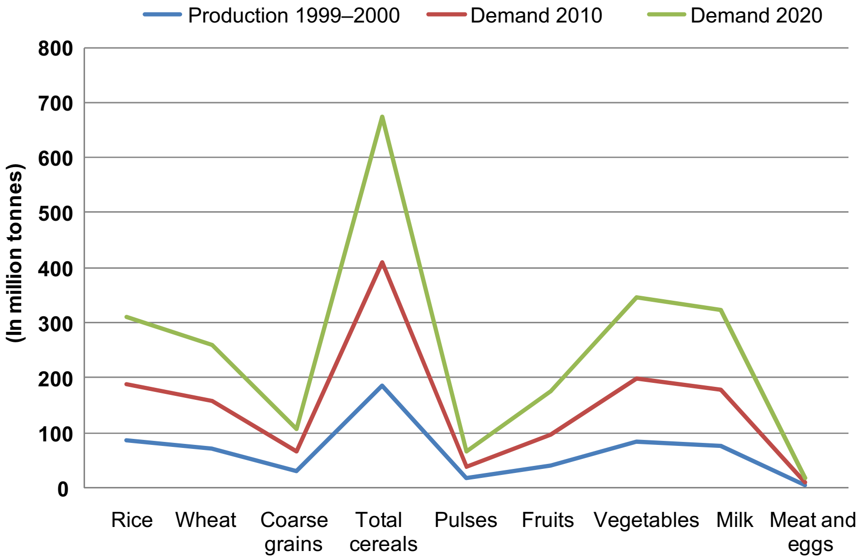


Figure 4 Food production and demand for key crops in India. Data source: Government of India (GoI), 2004: *Vulnerability Assessment and Adaptation, Chapter 3, India's Initial National Communication to the United Nations Framework Convention on Climate Change*, Ministry of Environment and Forests, GoI, New Delhi.

dependent on monsoons. Any changes in the rainfall and temperature extremes can impact the crop production and adversely impact their livelihoods. Since they do not have alternate sources of income as a coping mechanism, they are often forced to sell their assets such as livestocks, lands, or migrate in urban areas, where they have to settle in marginal and highly vulnerable areas. This increases the vulnerability and the situation of poverty. The situation is further grave for agriculture laborers. In India, about 50–75% of the labor population is dependent on agriculture. Increased vulnerability of agriculture to climate change will adversely impact the livelihoods of the small and marginal farmers, and the labor population who are highly dependent on this sector. It is necessary that along with improved agricultural facilities, these farmers and labor populations are provided with alternate sources of livelihood and social security, such as improved access to health care, education, and other facilities.

2.14.3 Existing Vulnerabilities

2.14.3.1 Over dependency on Agriculture

The agriculture sector in India is subjected to various stresses such as increased pressures for availability of land, water, and labor. This coupled with an increase in temperatures and precipitation will result in a negative impact on the food production. Although the share of agriculture in the country's GDP is 14.6% (GoI 2011) it contributes to approximately 45.5% of the employment (GoI 2010).

Considering the fact that approximately 67% of India's population depends on agriculture and related activities for livelihoods, a slow rate of growth of the agriculture sector is a concern. Hence, there is a need to diversify into other activities such as livestock farming. For instance, dairy and poultry enterprises could provide substantially higher financial returns than crop farming. Further, such enterprises can help create new jobs and bring about health and nutritional improvements in the families.

2.14.3.2 Requirement of Improved Infrastructure, Technology Transfer, and Extension Services

Practices adopted for increasing agricultural yield have turned out to be neither economically nor environmentally sustainable. Access to improved quality of infrastructure such as cropping technologies, seeds/crop sampling varieties, electricity supply, farm machinery, policy-based incentives, research in traditional farming methods, etc., will help in improving the crop production and reduce the vulnerability. Besides this, there is a need to develop forward and backward linkages with the traditional and modern technologies. For example, the crops grown using chemical fertilizers and genetically modified species, could lead to high risks, as these interventions could reduce soil fertility and lead to adverse health impacts. The crops grown using traditional knowledge and indigenous varieties may not pose such risks, albeit at a disadvantage of lower yields. This is where technology innovations and pilots are necessary.

There is a need to revisit the knowledge used in our traditional farming methods and update it to suit the current production requirements and climate variability. The linkages thus developed would help to reduce the technological gaps in farming. The farmers at the grassroot levels have often devised their own ways to meet the resource constraints posed due to adverse climatic situations of a place. The technological innovations carried by them are well rooted with the geography, climatic situations, and resource constraints. The techniques and methods are often simple, cost effective, and have a high potential to upscale. There is a need that such innovations are tapped and supported with necessary engineering technology, policy, and financial arrangements. Further, provision of extension services such as developing market linkages, access to credits for small and marginal farmers could help to reduce the financial vulnerability, and help in sustaining the high productivity on a long-term basis.

The technology transfer and adaptation at various levels with a collective approach of government, agriculture scientist, researchers, nongovernment and private sector agencies, and farmers will help to achieve this.

2.14.3.3 Gap in Demand and Supplies

One of the main challenges facing India is producing enough food for the increasing population. Import of basic commodities such as rice and wheat is increasing. Rapid increase in the population has induced additional stress on the food supplies. Since the land available for agricultural produce is limited, the focus has shifted to increasing the production capacity. This has led to the introduction of new crop varieties providing high yields. However, irrespective of these efforts, the shortage in food supplies is persistently increasing. This has led to increase in the prices of food grains and other agricultural commodities. There have been some adjustments by the government to control the escalation in the prices of major crops; however, the gap between the demand and supply is widening.

2.14.3.4 Dependency on Monsoons

Increased use of irrigation however has helped India increase average yields. About one-third of the cropland in India is irrigated, but rain-fed agriculture is still central to the economy. Harvests and national prosperity have traditionally depended on a successful south-west monsoon, which is the source of about three-fourths of India's annual rainfall.

As of 2010, only 40% of the net sown area of 141 MH has an access to irrigation, while the remaining 60% is rain fed (GoI 2011). For the areas, which are irrigated, the allocation of water is inefficient, unsustainable, and inequitable. This has reduced the potential of growing multiple crops within a year.

Further, the monsoonal rainfall is very inconsistent and unevenly distributed. Increased variability of the summer monsoons has directly impacted the agriculture yield. The National Commission on Agriculture in 1976 has estimated that the rainfall variations accounted for 50% of the variability in agricultural yields, being as high as 90% for cotton and groundnut, 47% for wheat, and 45% for barley and jowar. Since the majority of the rain-fed varieties is grown in small landholdings, it has a direct impact on the livelihoods of the small and marginal farmers whose earnings are largely dependent upon the net crop produced during this time.

2.14.3.5 Disaster-Related Vulnerabilities

Increase in the frequency of disasters will entail higher economic and financial risks for farmers. Disasters such as droughts and floods have resulted in huge economic losses. In India, two-thirds of the total area under cultivation is prone to droughts and about one-fourth of the cropland is prone to flooding. As per the study conducted by National Center for Disaster Management (NCDM) and National Disaster Management Division (NDMD), in 1999, 40 MH of land is prone to floods and about 30 million people are affected each year on an average (NCDM and NDMD 1999).

The capacity to restore the livelihoods and initiate new livelihood options is rather low. In addition, new disease vectors may proliferate that could further reduce the capacity of earnings from livestock and related sources.

The adaptive capacity of the farmers mainly depends upon the farmer's socioeconomic condition and the access to infrastructure, finances, and insurance. As per a study conducted by TERI (2003), it was found that except for the State of Bihar, all the districts falling under the Indo-Gangetic plains have a higher adaptive capacity. The adaptation capacity is found to be extremely low for the states of Rajasthan, Gujarat, Madhya Pradesh, and western parts of Maharashtra, Andhra Pradesh, and Karnataka. Vulnerability of the north, north-eastern, and southern states is lowest. The study reveals that districts, which are highly sensitive to the climatic variables, are not necessarily the ones with high vulnerability and vice versa (O'Brien et al. 2004).

2.14.3.6 Biophysical Vulnerability

The agriculture produce in India largely depends on large irrigation projects and use of chemical fertilizers for increasing the harvest. While doing so, conservation of natural soil nutrients, water resources, and water holding capacity are largely neglected. Clearly, this type of practice is not sustainable as it leads to degradation and contamination of land resources on a long run. The crops grown by making use of excessive chemicals extract more water and do not recharge the groundwater. In order to extract more production, the crops grown were of the same varieties, which extract the soil nutrients, unlike traditional cropping where crops are grown on a rotational basis and intercropping is done to increase the crop variety.

The life cycle assessment of this cropping shows that due to the presence of harmful chemicals the residues of such crops cannot be used for any other purpose such as fodder for cattle. The use of sprays and chemicals to increase production kills the bacteria and fungus in the top soil layer thereby reducing the fertility of the soil and its capacity to grow the next crop. **Although increasing the food production is important, achieving it in a sustained manner is equally important. Production should be increased without damaging the soil nutrients and water. The focus therefore has to shift from high yield giving chemical fertilizers to the sustained yield given by organic fertilizers.**

2.14.3.7 Slow Growth in Agroeconomy

Although agriculture is the backbone of India's economy, dependency on agriculture for employment is decreasing gradually. Sustenance of small and medium farmers is difficult, if appropriate policies and programs along with a strong institutional delivery system are not developed in time.

As discussed earlier, the current agricultural practices are neither economically nor environmentally sustainable. This has resulted into poor yields and increase in commodity prices. Poorly maintained irrigation systems and almost a universal lack of good extension services are among the key factors responsible for the slow growth of the agriculture economy. Further, the farmers are not able to get the right price for their produce as their access to markets is hampered by poor roads, rudimentary market infrastructure, and excessive regulation (The World Bank 2008).

2.14.3.8 Low Productivity

Since the cultivable area is limited the focus is on enhancing the crop yield or productivity. However, it has been observed that the productivity is high only for large and medium landholdings and having an access to irrigation facilities; whereas the production of small and marginal landholdings continue to remain low.

A study conducted by The World Bank (2008a) suggests that there are multiple reasons behind the low productivity in agriculture sector. One of the main reasons is **the large number of agricultural subsidies that has in fact reduced the productivity–enhancing investments. The technologies for improved and sustained food production are being used to a limited extent. A widespread knowledge of such technologies has also been missing. The main reasons for these impediments are high costs, illiteracy, slow progress in implementing land reforms, inadequate or inefficient finance, and marketing services for farm produce, and impracticality in the case of small landholdings.**

2.14.4 Impacts of Climate on Agriculture

Agriculture is extremely sensitive to the impacts of climate change. A small variation in the rise/fall in temperatures and precipitation levels can reduce/damage the crop growth. The carbon dioxide concentration in the atmosphere also has a significant impact on the growth of the crops.

These impacts can be broadly classified as direct, indirect, and socioeconomic impacts. The direct impacts are the ones, which are felt through direct changes in temperature, water balance, carbon dioxide concentrations, and extreme weather events. These parameters can have an adverse effect on growth, structure, and life cycle of the crops. The indirect impacts are shown with the outbreak of crop diseases, decrease in the quality and quantity of crop production, reduced fertility of soil, emergence of pests, weeds, insects, diseases, etc. The socioeconomic impacts are the cumulative effect of both the direct and indirect impacts. This includes shortages in food supplies, loss of livelihoods, reduced income, increased exposure to disease vector, etc. Figure 5 represents the linkages between these impacts and development of adaptation and mitigation strategies.

According to IPCC fourth assessment report (IPCC 2007), the earth's temperature has increased by 0.74 °C between 1906

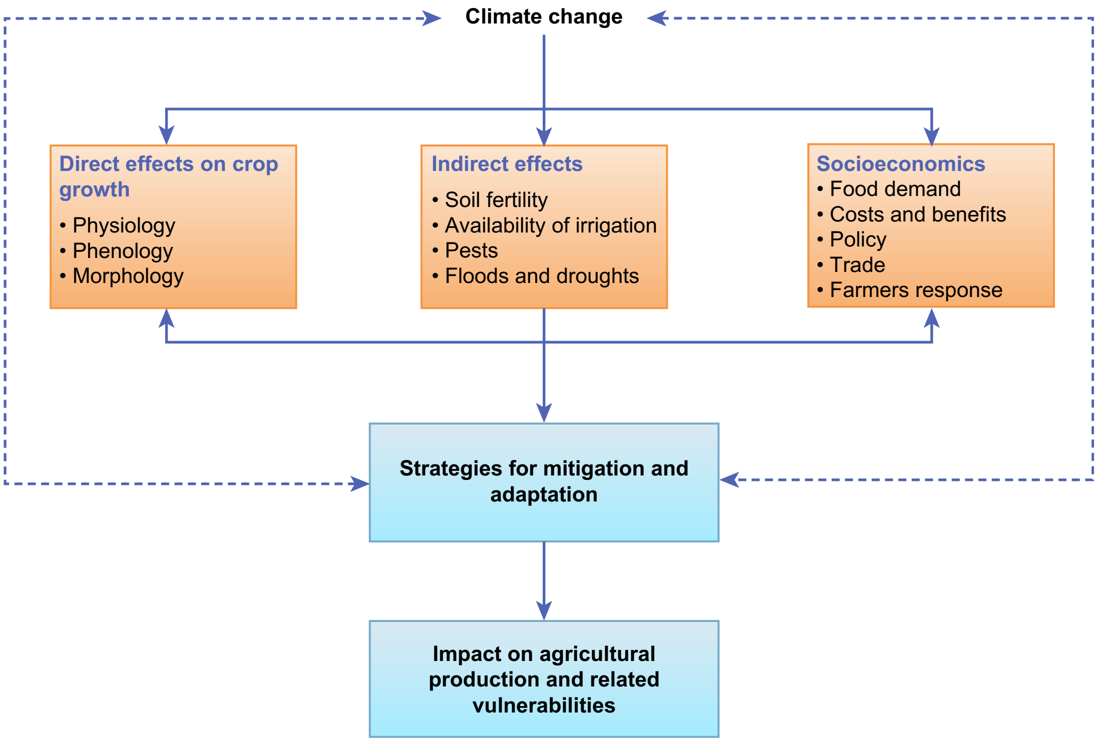


Figure 5 Assessment of vulnerability of agriculture to climate change. Adapted from Department of Environment Food and Rural Affairs (DEFRA), 2009: *Climate Change Impacts on Agriculture in India*. Department for Environment, Food and Rural Affairs, Government of United Kingdom. [Available online at http://www.decc.gov.uk/assets/decc/what%20we%20do/global%20climate%20change%20and%20energy/tackling%20climate%20change/intl_strategy/dev_countries/india/india-climate-6-agriculture.pdf, retrieved on 12 July 2010.]

and 2005 due to increase in anthropogenic emissions of greenhouse gases. It is estimated that the increase in temperature will result in 10–40% decrease in production of food grains by AD 2100.

In the case of India, the temperature data collected by the Indian Meteorological Department (IMD) for the last 100 years show warming of 0.5 °C over Indian region (GoI undated). The future climate change projections for 2070–2100, based on application of PRECIS by Indian Institute of Tropical Meteorology (IITM), suggest a change of 3–5 °C, in the annual mean surface air temperature and a 20% rise in the summer monsoon rainfall.

In the case of Rabi and Kharif crops, the mean temperature is projected to increase by 0.10–0.30 °C in Kharif (summer) and 0.30–0.70 °C in Rabi (winter) by 2010 (IPCC 1996). There is a possibility that this trend may increase in 2070 where the mean temperatures during Kharif and Rabi seasons will fall between 0.40–2.00 °C and 1.10–4.50 °C, respectively (GoI 2004). Table 1 presents an assessment of the relationship between decreasing rainfall and net production of Kharif crops in the years of deficient rainfall. It has been observed that for an average deviation of 17% rainfall, the corresponding change in food grain production is about 11%. The mean rainfall is projected not to change by 2010, but has a possibility to increase by 10% by 2070 for the Rabi season. At the same time, there is an increased possibility of climate extremes, such as the timing of onset of monsoon and increased intensity and frequencies of droughts and floods (GoI 2004).

2.14.4.1 Sensitivity of Indian Agriculture to Climate and Possible Changes

Climate change can adversely impact the production of crops such as wheat, rice, and pulses in India. It is projected that there is a possibility of about 10–40% loss in crop production in India by 2080–2100 due to global warming (Fischer et al. 1994; IPCC 2007). Also a few other Indian studies by Aggarwal

Table 1 Impact of rainfall variation on crop production for Kharif season in India

Deficient rainfall years	*Monsoon rainfall % departure from normal*	*Rainfall in July*	*Kharif food grain production % fall*
1972–73	−24	−31	−7
1974–75	−12	−4	−13
1979–80	−19	−16	−19
1982–83	−14	−23	−12
1986–87	−13	−14	−6
1987–88	−19	−29	−7
2002–03	−19	−49	−19

Source: GoI (2003): Economic Survey 2002–03. pg. 157, Economic Division, Ministry of Finance, New Delhi as cited by Kelkar, U., 2006: Indian agriculture: growth, sustainability and vulnerability-chapter 3. *IISD-TERI-IDRC Report Designing Policies in a World of Uncertainty, Change and Surprise, Adaptive Policies Project.* International Institute for Sustainable Development (IISD), The Energy and Resource Institute (TERI) and International Development Research Centre, Canada and New Delhi, 40–41.

and Sinha (1993), Saseendran et al. (2000) and Aggarwal and Mall (2002) confirm a similar trend.

Table 2 presents highlights of the various studies undertaken to assess the impacts of climate change on Indian agriculture. Almost all these studies confirm that the economic losses to agriculture will increase and will be significant.

About 1.5–2° increase in temperatures will heavily impact the production of wheat, whereas increasing levels of precipitation will impact the cultivation of rice. As per the study conducted by Aggarwal et al. (2009), for every 1° rise in temperatures, the possibility of losses in the wheat production is estimated to be about 4–5 million tons. In the IPCC third assessment report, a study conducted by Saseendran et al. (2000) stated that with 1.5° rise in temperature and 2 mm increase in precipitation, the yield of rice is expected to decrease by about 3–10%.

The food production in the coastal areas especially the coastline along Gujarat and Maharashtra along with parts of Rajasthan, North Karnataka, and Andhra, Madhya Pradesh is expected to be impacted more than other states. In 2004, there were instances of reduction in the crop production, in the Indo-Gangetic plains due to a rise of 3–6 °C, i.e., about 1 °C per day over the whole crop season. This led to about 10–20 days of early maturity of the crops, thereby reducing the overall wheat production by 4 million tons (Samra and Singh 2004 as cited in GoI 2010a 67 pp.).

In certain cases, the increase in carbon dioxide levels is expected to increase the crop production, however, there is a possibility that it would be nullified by the increase in temperature.

2.14.4.2 Impacts on Food Crops

The study conducted by the Department of Environment Food and Rural Affairs, DEFRA (2009), for understanding the impacts of climate change on India's agriculture shows that due to low coping mechanism in rain-fed agriculture, the reduction in yield as a result of climate change is predicted to be higher for rain-fed crops as opposed to irrigated crops. The difference in yield will be determined by the actual climatic situation. It is estimated that the probable losses will be high for areas where the baseline temperatures are higher. For regions where the temperature is relatively low, the yield is expected to decrease by about 1.5–5.8% (GoI undated).

The major food crops in India include wheat, rice, millets, and sugarcane. Studies have been undertaken to assess the climate change–related impacts on these. The study undertaken by Aggarwal et al. (undated) at the Indian Agriculture Research Institute (IARI) shows that wheat production in 2020 is set to decline. Production levels may increase up to 5% in the states of Haryana, Uttarakhand, parts of Uttar Pradesh, and Jharkhand. In some pockets of Uttar Pradesh and Uttarakhand, the increase is estimated to be 10%. The losses of wheat production will be predominantly felt in the regions of central Maharashtra, western Gujarat, and Rajasthan. In the absence of any adaptation measures, the trend is expected to further decline by 10–20%. The findings of this study are presented in Figure 6. The assessment of the results across various regions depicts that the production of wheat in the northern region will increase in the initial period (2020). However, this rise will be followed by a decline where the production may get reduced by 5000 tons. The amount of increase and decrease in the wheat production across four regional territories is presented in Figure 7.

India is the world's second largest producer of wheat and rice. About 20% of the world's rice production comes from India. Most of the country's rice produce comes from the southern states especially Andra Pradesh, coastal areas of Maharashtra, West Bengal, and Uttar Pradesh.

Rice is a water extensive crop. Delays in the arrival of summer monsoon and fall in night temperatures can have a negative impact on the country's rice production. Every 1° fall in night temperatures can reduce a 10% yield (Peng et al. 2004). Also spells of erratic and unseasonable rains can lead to about 50–100% yield loss (Annamalai and Shekar 2009).

Table 2 Assessment of climate-related impacts on India: key findings from various studies

GoI (2004)	● Wheat yields in central India may drop by 2% in a pessimistic climate change scenario. ● Decline in yields are offset by increase in carbon dioxide concentrations with the magnitude varying from one crop to the other in different regions, depending mostly on the scenario chosen.
TERI (2003)	● Districts in western Rajasthan, southern Gujarat, Madhya Pradesh, Maharashtra, northern Karnataka, northern Andhra Pradesh, and southern Bihar are highly vulnerable to climate change in the context of economic globalization. ● Numerous physical (i.e., cropping patterns, crop diversification and shifts to drought-/salt-resistant varieties) and socioeconomic (i.e., ownership of assets, access to services, and infrastructure support) factors come into play in enhancing or constraining the current capacity of farmers to cope with adverse changes.
IPCC (2007)	● Temperature rise of 1.5 °C and a 2 mm increase in precipitation could result in a decline in rice yields by 3–15%. ● Sorghum yields would be affected and yields are predicted to vary from 18 to −22% depending on a rise of 2–4 °C in temperatures and increase by 20–40% of precipitation.
Kumar and Parikh (1998)	● Economic impacts would be significant even after accounting to farm-level adaptation. The loss in net revenue at the farm level is estimated to range between 9 and 25% for a temperature rise of 2–3.5 °C.
Sanghi, Mendelsohn, and Dinar (1998)	● A 2 °C rise in mean temperature and a 7% increase in mean precipitation would reduce net revenues by 12.3% for the country as a whole. Agriculture in the coastal regions of Gujarat, Maharashtra, and Karnataka will be the most negatively affected. ● Possible losses are pointed out for the major food-grain producing regions of Punjab, Haryana, and western Uttar Pradesh.

Adapted from Kelkar, U., 2006: Indian agriculture: growth, sustainability and vulnerability-Chapter 3. *IISD-TERI-IDRC Report Designing Policies in a World of Uncertainty, Change and Surprise, Adaptive Policies Project*. International Institute for Sustainable Development (IISD), The Energy and Resource Institute (TERI) and International Development Research Centre, Canada and New Delhi, 40–41.

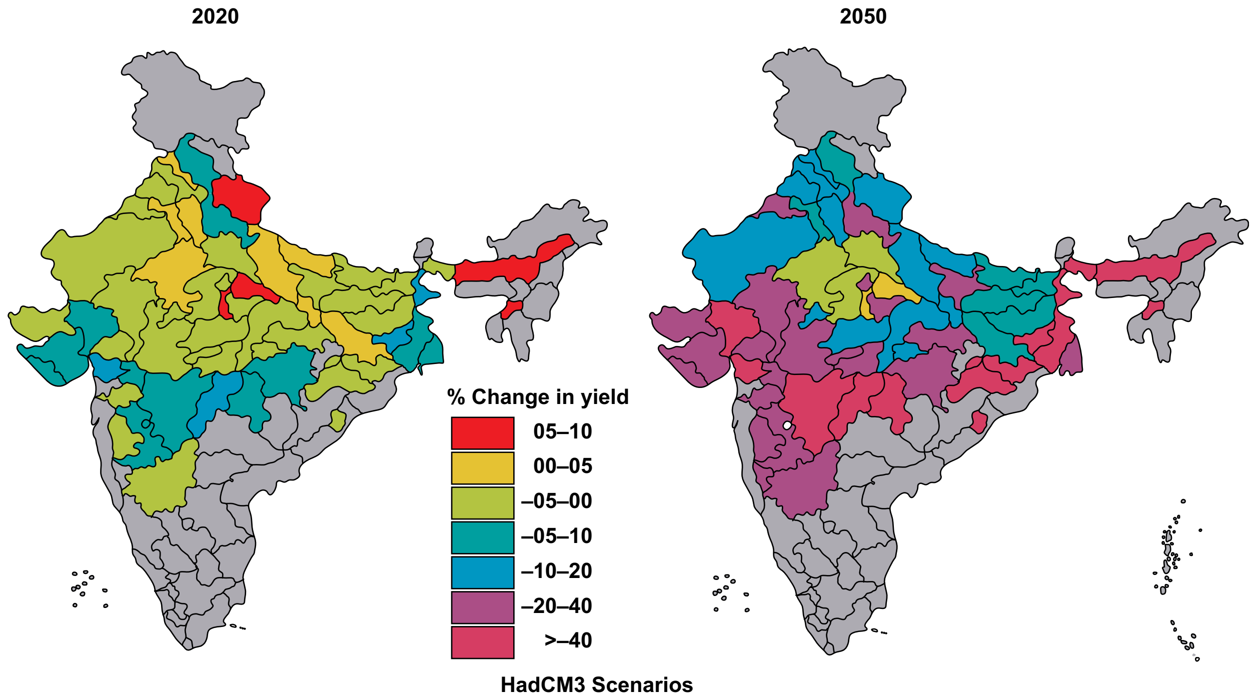


Figure 6 Percentage change in production of wheat in a pessimistic technology scenario using outputs from climate model HadCM3. Source: Aggarwal, P. K., et al., undated: *Vulnerability of Crop Yields in India to Climate Change*. Indian Agriculture Research Institute, New Delhi, India. [Available online at http://www.teriin.org/events/docs/wb_confer/73pk_agarwal.pdf.]

Other impacts, which would be mostly prevalent in the coastal belt include increased salinity, due to intrusion of sea water and increased flooding.

The study conducted by Aggarwal et al. (undated) from IARI has calculated the net loss in production in 2020, 2050, and 2080. The bar chart presented in Figure 8 suggests a possible loss of 2.5% by 2020. The loss may increase to over 7% by 2050 and may go as high as 25% by 2080, which can become a major threat to food crisis since rice has a major share in the country's crop production. Timely adaptation measures can help to reduce the intensity of losses in future to a great extent. Figure 8 shows the reduction in the amount of losses expected after starting adaptation.

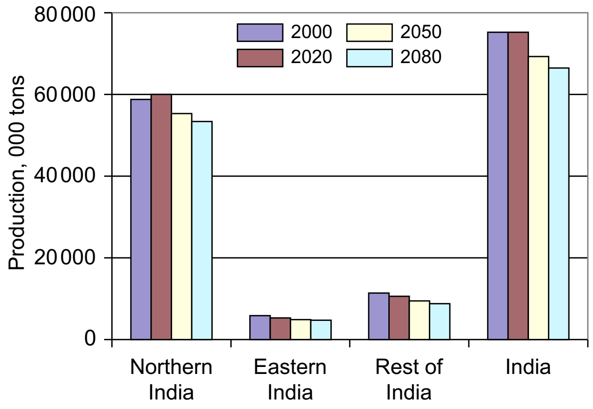


Figure 7 Estimated wheat production across four regional territories for 2000, 2020, 2050, and 2080. Source: Aggarwal, P. K., et al., undated: *Vulnerability of Crop Yields in India to Climate Change*. Indian Agriculture Research Institute, New Delhi, India. [Available online at http://www.teriin.org/events/docs/wb_confer/73pk_agarwal.pdf.]

Amongst the other crops sugarcane and millets are some of the main food crops. Study conducted by the World Bank (2008) in the states of Maharashtra, Andra Pradesh, and Orissa shows that yields may drop by/up to 30%. India is the world's largest millet producer. The requirement of water for these crops is about 25% less in comparison to the main stream crops such as rice and sugarcane. Also, they can adapt to a wide range of ecological conditions and can be grown in all seasons. Millets can be grown in the poorest of the soils and are pest free. They do not require pesticides and fumigants for storages. Their growth is better in the absence of chemical fertilizers and grows mostly on farm land and biomanure. Millets have high nutritional value. While wheat and rice might provide only food security, millets produce multiple securities (food, fodder, health, nutrition, livelihood, and ecological) thereby increasing the agriculture security (Millet Network of India 2009). However, it is observed that the area for millet cultivation in India is shrinking, which is a concern. Considering the fact that millets are water saving and drought tolerant, it is important that they are promoted.

2.14.4.3 Impacts on Biodiversity

The change in temperatures and humidity will influence the biodiversity of a region. Insects and pathogens will change their behavior. Considering that crops are dependent on insects for pollination, the change in behavior will impact the yield of

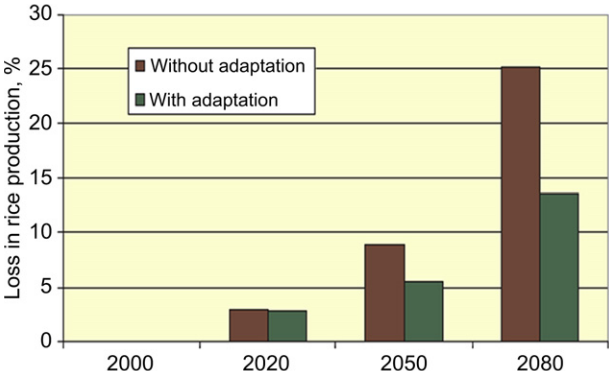


Figure 8 Possible impacts on rice production. Source: Aggarwal, P. K., et al., undated: *Vulnerability of Crop Yields in India to Climate Change*. Indian Agriculture Research Institute, New Delhi, India. [Available online at http://www.teriin.org/events/docs/wb_confer/73pk_agarwal.pdf.]

crops. In the case of crops such as sesame, litchi, mustard, and cashew the yield is substantially high when pollinated by insects. While crops such as sunflower, cloves, melons, beans, etc., are completely dependent on pollination by insects. The temperature changes can also influence growth of weeds and pathogens, which can further reduce the agricultural produce.

2.14.4.4 Cross-Sectoral Impacts

Rural livelihoods and many ancillary industries are dependent on agriculture. Impacts on agriculture sector are multifaceted and raise concerns regarding food safety, food and water security, animal welfare, and environmental protection. Allied agriculture processing industries and sectors such as poultry and dairy are also closely linked. Chemical industries manufacturing pesticides and fertilizers heavily depend on the growth of agroeconomy.

The rural non-farm economy that is seen as a great prospect for livelihood creation is closely linked with agriculture. A large share of rural manufacturing involves production and supply of farm inputs and agroprocessing. Rural services target farmer's needs. Any reduction in farm production will directly impact the rural non-farm sector. Also in India, rural areas are seen as future markets by the manufacturing and the service sector. Good road connectivity and telecommunications have opened up the agricultural markets. Today, rural areas are vibrant markets for the Fast Moving Consumer Goods (FMCG), consumer durables, telecommunication, and financial and insurance services. Any decrease in farm productivity would lead to decreased demand in the otherwise burgeoning Indian manufacturing and service sector.

2.14.4.5 Significance of Local Knowledge and Technologies in Combating Climate Change

People in vulnerable areas, often find simpler ways to adapt themselves to the climate adversities. These innovations are low cost and high potential to upscale. It is important that this knowledge is mined and used to its advantage in similar situation across the country. Some of these innovations would require technical support and refinement before upscaling, while others could be directly shared within communities as best practices. Box 1 illustrates two such cases where communities and individual have gone beyond their limitations and found new ways and manners of combating adversities.

2.14.5 Strategies for Adaptation and Mitigation

2.14.5.1 Increasing Investments in Agriculture Infrastructure

Considering the fact that two-thirds of India's population is dependent upon agriculture, it is important that the sector is made more competitive, efficient, profitable, and less vulnerable. The traditional approach of intensive production and subsidies has to be changed to sustained production and investments. Investments for improving road networks, canal irrigation, power supply, market linkages, improved land, and water management techniques, etc., will help to build resilience and therefore reduce the climate change–related vulnerabilities.

The use of excessive fertilizers and use of technologies for gaining intense production of food crops has resulted in reducing the capacity of soil to provide sustained food production on a long-term basis. The situation is expected to get worse with climate change. Keeping this in view, there is a need for making investments in low risk alternatives, which can help in giving production in a sustained manner. This would include making increased investments in organic agriculture. Promoting organic agriculture will help to conserve the soil nutrients and help to increase the production in a sustained manner. Developing a system of pest control, for reducing the resurgence and migration of pests will stop/reduce losses during production.

2.14.5.2 Developing New Technologies and Innovations

Climate change will impose new challenges for technological innovations to be brought in the agriculture sector. This would include development of new varieties of crops, which can resist the increased trend of warming and increase the productivity without reducing the soil fertility and nutrient content. This would require undertaking research in climate resilient varieties of crops, development of water, and carbon conservation practices. For improving the net output, diversification of crops, increasing opportunities in the allied sectors of farming such as

Box 1

Use of grassroots innovations for reducing vulnerability in agriculture.

Enhancing Production in Varied Situations for Diversified Cropping

The tribal communities residing in the hilly belt of Western Ghats and Dimbhe dam catchment area have devised an innovative method for increasing their agriculture and fish production with support from Shahwat Trust. "About 350–400 ha of land is available for agriculture every year in the submergence area of the Dimbhe reservoir. This land gets submerged in the rising waters of the Dimbhe reservoir when the dam starts to fill up in Jul.–Aug. every year." Shahwat (2008).

After the monsoons, when water from the Dimbhe reservoir is released, the area under submergence having shallow water levels opens up in patches. The tribal people residing near the dam practice drawdown cultivation in these lands. The land remains open for some time and gets submerged when the water table of the dam rises during monsoons. During monsoons, when the water table rises, the same area is used for fishing purpose. The nutrient quality of the soil, in the submergence area is very low. Due to this, the productivity of the crop becomes reduced. The low organic content in water reduces the aquatic productivity and the fish catch during monsoon season. To increase the soil fertility, green manure crops such as Dhencha and Taag were planted. The seeds were sown immediately after the first rains. By the time the seeds grow to about 2–3 ft height in 45–50 days the water table starts increasing. After 1.5–2 months (mid July) water table rises, the leaves of these plants start getting dissolved and decompose forming a green manure. This acts as organic matter for the fish to feed.

The root nodules of this plant allow the growth of nitrogen fixing bacteria in the soil. Due to this, the fertility level of the soil is increased. When the land is again free from submergence it can be put to agricultural production. It was observed that the production levels increased from 3 to 5 quintals.

Courtesy: Prof. Anand Kapoor, SHASHWAT, Pune.

* Shahwat Trust is a grassroots initiative developed in response to challenges faced by indigenous tribal people in the Pune District of Maharashtra, India.

Shashwat Trust, P.O. Manchar, Dist. Pune 410 503, Maharashtra, India.

Increasing Cotton Production in Drought Prone Areas in Jalgaon District in Maharashtra

Local techniques and processes are not only frugal and affordable, but also sustainable (Gupta 2010). The poor often have to live on the edge, and frequently resort to creative ways to combat climate adversities. This is a case of Ms. Pramila and Vikas Shinde who own half hectare land in Pingalwada village of Jalgaon district in Maharashtra.

The area is water scarce and the couple did not have enough financial resources to support a bore well and drip irrigation in their farm. Vikas's wife, Pramila found a new way to optimize the cotton production in her farm. She started growing cotton seeds in plastic bags. Approximately 1 month before the sowing time, she took the bags in the farm and looked after them for 1 month. Pramila kept them in a tree shade in her farm and watered them daily. The seedlings were thus irrigated with limited water. By the time, the monsoons arrive in June, instead of sowing the seeds, Pramila transplanted the grown samplings. While the raw seeds were planted in other farms, grown samplings were transplanted in Pramila's farm. The samplings grew faster and the production increased to 2.5 times. The innovation not only reduced the water requirement for the crop, but also increased its productivity.

Source: Excerpted from a case study done for sristi.org under the Grassroot Innovations for Inclusive Development (GRIID) project under the academic guidance of Dr Anil K. Gupta, Indian Institute of Management Ahmedabad (IIMA).

livestock, fisheries, horticulture, and other such combinations will help the farmers to earn some extra income and reduce the gap due to economic losses. Since the science of climate change is evolving, the extent of research carried out for understanding the impacts for various agroclimatic regions is limited. Under such situation, the adaptation strategies should focus on providing no regret solutions that can reduce the existing vulnerabilities and build resilience.

There is an increased need for conducting a high rigor research in climate change and agriculture. Currently, most of the work is being carried out by foreign institutions, which are based on large scale extrapolation of the results obtained on a global scale. The results thus obtained can be misleading since they do not consider the regional climatic features of that place. To make an accurate assessment, it is necessary to build a model which is based on a local situation and draws from the global parameters of climate. This is important since the change in inter- and intraannual variability helps to improve the adaptive response. Understanding the intensity of impacts at local scale will help to formulate better adaptation strategies for the specific location/place.

One of the main aspects of climate change adaptation is to make use of the local technologies and innovations, which have been used in the rural areas traditionally to combat the worse situation. These technologies/practices are often low costs and do no harm to the soil. It is important that these practices and technologies get documented and a detailed scientific research is conducted to improvise the gaps if any. There is a high potential that some of them could be scaled up to benefit the communities.

2.14.5.3 Provision of Extension Services

To meet the changing information and technological needs of framers, there is a need for development of new organizations in extension delivery. Such organizations will particularly focus on providing extension services in agriculture to rural poor who are most vulnerable to the negative impacts of climate change. The extension services will cater to the changing information and technological needs in agriculture, developing institutional, market linkages, and increased scientific knowledge.

2.14.5.3.1 Creation of Rural Information Centers

It has been seen that a focus on purely increasing food production is not enough to cater to the needs of the growing population. Several districts in India with high agricultural productivity levels also show high levels of poverty (Haque 2000). It is important to focus on the vulnerable communities i.e., the farmers having small landholdings. These farmers have low access to information and technologies. Further, the net quantity of production from small landholdings is so low that the farmers are not able to get a direct access to markets.

Information centers in rural areas that can advise the poor farmers on what has to be grown in case of seasonal changes and extreme events such as cold and heat waves or flood, and when drought like situation arise. These centers can offer advice on land use, cropping systems to adjust to the changes. These centers will also provide information about the existing trends of market prices and link them to various entrepreneurial hubs where the net produce could be sold at an assured price. A network of such centers linking from district to national levels can help in providing continuous technological support and knowledge to the farmers.

2.14.5.3.2 Developing Institutional Linkages

Under the present scenario, the interlinkages between various institutions working in the area of climate change research, policy, funding, etc., are rather weak. These interlinkages between institutions at various levels, including the Rural Information Centers as earlier proposed will help to strengthen knowledge and facilitate resource sharing. A network of agencies at state, national and international levels should be created for sharing scientific data, best practices, and technological innovations in agriculture to respond to climate change. Establishment of region-specific climate centers will further help to deliver solution and support to farmers in that region by providing access to new technologies and crop varieties.

2.14.5.4 Hazard Proofing

2.14.5.4.1 Establishment of Early Warning System

A slight variation in the temperatures and/or precipitation can affect the crop production. Establishing early warning systems will help to receive the information about weather-related changes especially for the extreme weather events.

2.14.5.4.2 Provision of Insurance Services

There is an increased requirement of providing security to the farmers since the chances of the crop failure have increased. Enabling policies that encourage farm insurance can provide protection from adverse effects on farm production due to natural calamities.

2.14.6 Concluding Remarks

Agriculture sector in India is highly climate sensitive. With the increasing impacts of changing temperatures and precipitation levels, adaptation is crucial for food security and sustenance. In order to make the adaptation practices effective, a systems approach is necessary that follows a multi-pronged approach. The scope and emphasis of current agricultural policies and programs in India is myopic. These programs are often implemented as isolated interventions, not factoring benefit sharing and engagement of farmers and other stakeholders. The cross-sectoral impacts are largely neglected. The Indian agricultural sector needs a facelift where the conventional approach of subsidies and grants should be transformed to simulating investment flows and promoting entrepreneurship. Here technology innovation based on local knowledge is very important. Creative ways and innovations at community levels should be recognized, researched, and blended with modern science and communication technologies.

All these measures will help in building national capacities and resilience and help reduce the vulnerability of small and marginal farmers.

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2.15 Response of the Amazon Tropical Forests to Deforestation, Climate, and Extremes, and the Occurrence of Drought and Fire

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2.15.1 Introduction

To the extent that many studies of the last two decades deepen the understanding about the Amazon tropical forest and more is known about the environmental services it offers, they also increased our level of awareness about the growing threats that this system has been subjected to. In addition to the process of uncontrolled expansion of the agriculture frontier, the Amazon, for its large scale, is an ecosystem highly susceptible to climate at regional and global scales. This chapter addresses issues related to environmental drivers of change in the Amazon: deforestation, climate, climate extremes, and fire. The goal is to present aspects of a synergistic action of these effects and the possible responses of Amazonian ecosystems to these drivers of change: (1) short-term responses as the mortality of some species (biodiversity loss), loss of living biomass with consequent influence on storage, and exchanges of carbon with the atmosphere to (2) long-term responses, such as 'savannization' and Amazon dieback. On the other hand, it has been hypothesized that the forest may show some degree of resilience to tolerate those impacts before starting to respond with degradation of the ecosystems. One of the challenges of Amazonian science today is to find out how close those drivers might be from exceeding 'tipping points' of stability of the Amazonian system. We first review the response of tropical forests in Amazonia to isolated drivers of environmental change, and then analyze potential synergistic effects and forest responses from the perspective of the timescale that they might occur. **Figure 1** depicts the framework of analysis for this review, based on synergistic interactions between major drivers and corresponding physical and ecological responses.

2.15.2 Deforestation

It has been widely recognized that deforestation is the most direct and possibly the most deleterious threat to Amazon ecosystem functioning. Until the 1970s, the 6.2 million km^2 of the Amazon forest remained relatively intact. As a result of government plans for development of the region, deforestation rates began to rise. Incentives for the development of the Amazon region have become incentives for deforestation since then; to encourage the planting of extensive pastures and provide tax incentives for active companies in the region, the government would accept as evidence the removal of vegetation cover (Lima 2005). That took place from the early 1970s to the early 1990s.

From 1978 to 1988, when the National Institute for Space Research (INPE) began calculating estimates of annual deforestation rates, the 10-year average deforestation rate was about 21 000 km^2 year^{-1}. Since then, the rate has oscillated because of the variation in market prices of the main driving forces of deforestation in the region (e.g., timber, cattle, soybeans) and owing to the environmental constraints (**Figure 2**).

Another human activity driving the Amazon forest degradation comprises selective logging. According to Asner et al. (2005), not necessarily the areas degraded by selective logging coincide with fully deforested areas. Selective logging is, therefore, a distinct form of land use in the Amazon. Between 1999 and 2002, selective logging has affected an area greater than 12 000 km^{-2} year^{-1} (Asner et al. 2006). According to INPE, 15 000 km^{-2} of forested areas has been degraded by selective logging in 2007 and 25 000 km^{-2} in 2008.

The Brazilian Amazon occupies nine different nations, but around 80% of deforestation occurs in Brazilian territory

http://dx.doi.org/10.1016/B978-0-12-384703-4.00228-8

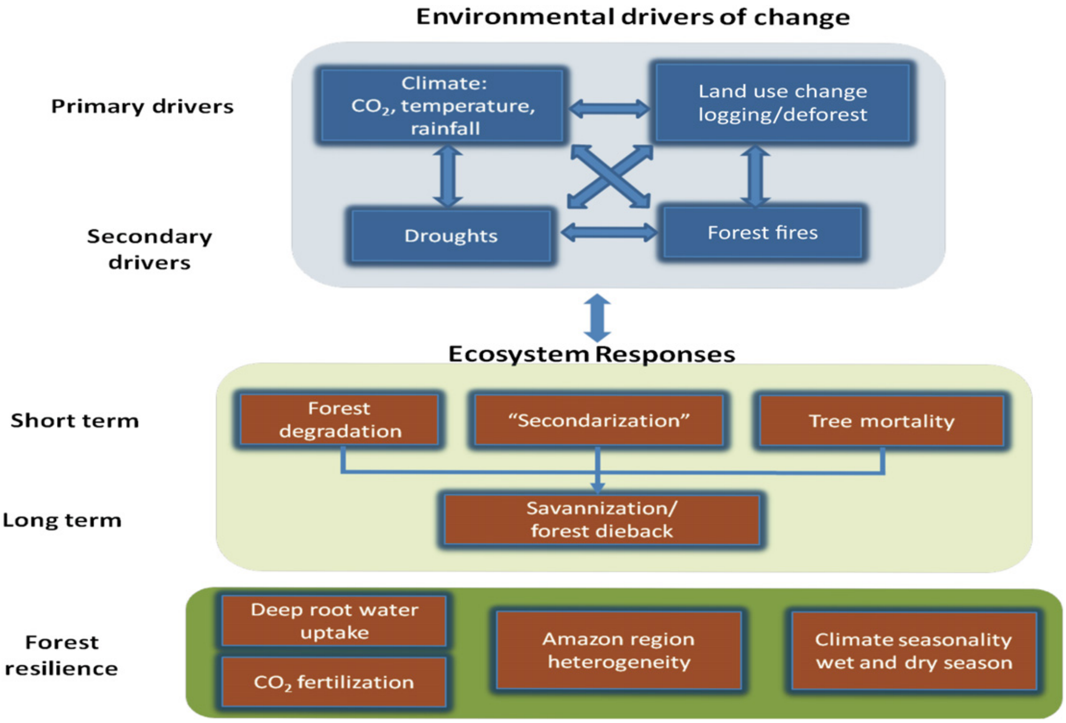
Environmental drivers of change
Primary drivers
Climate: CO_2, temperature, rainfall
Land use change logging/deforest
Secondary drivers
Droughts
Forest fires
Ecosystem Responses
Short term
Forest degradation
"Secondarization"
Tree mortality
Long term
Savannization/ forest dieback
Forest resilience
Deep root water uptake
CO_2 fertilization
Amazon region heterogeneity
Climate seasonality wet and dry season

Figure 1 Anthropogenic drivers acting on the Amazon forest, ecosystem responses, and some aspects of forest resilience.

(Soares-Filho et al. 2006), mainly in the transition zones between savanna and rainforest – southern and eastern Amazon regions – the so-called 'arc of deforestation.' Also at global level, deforestation of tropical forests occurs in hot spots of deforestation, because 50% of deforestation of tropical forests has occurred in only 6% of the forest as a whole (Hansen et al. 2008).

Although soybeans have been assuming increasing importance in the grain market (Nepstad et al. 2008; Sawyer 2008), about 70% of the deforested area in Amazonia has been converted into pasture (Soares-Filho et al. 2006). Another important driving of deforestation rates in Amazonia is paved (Soares-Filho et al. 2006) and unpaved (Perz et al. 2008) roads. Projections indicate that deforestation if left unchecked could

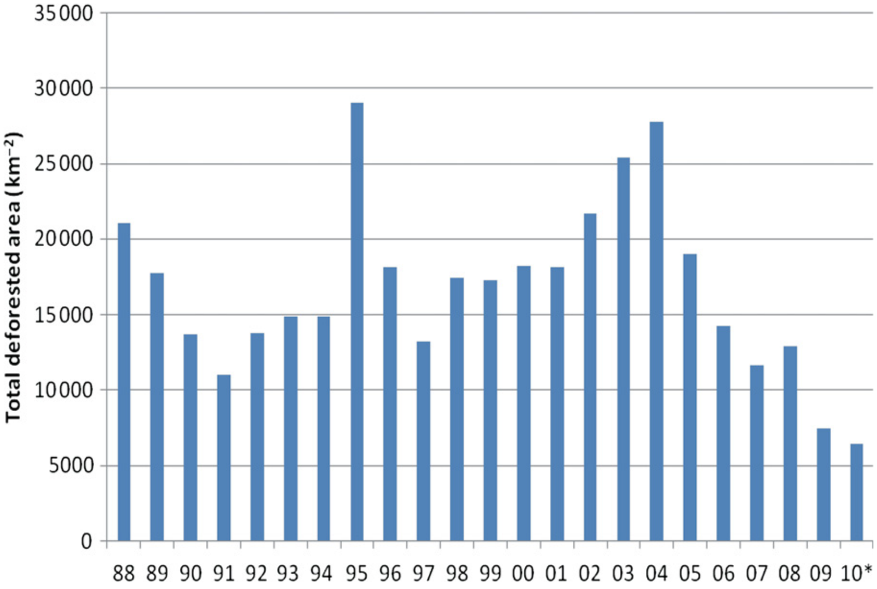

Figure 2 Total annual deforested area according to INPEs (National Institute for Space Research) PRODES program – [Available online at http://www.obt.inpe.br/prodes/index.html].

reach between 30 and 50% of the rainforest area by 2050, even considering the existence of legislation to maintain and protect forest reserves (Soares-Filho et al. 2006).

2.15.2.1 Forest Response to Deforestation and Selective Logging

As a result of deforestation, forest areas are transformed into degraded forest, pasture, and agricultural areas, and may or may not culminate in secondary vegetation areas. This suppression of vegetation can lead to the action of other threats to the Amazon forest, such as increased fire spread and regional climate change. By being a process that begins with the intact forest and ends with the complete conversion of the original forest into other types of land cover, one could imagine that deforestation is a process that occurs suddenly. However, deforestation does not imply an immediate change of the forest landscape in an area of bare soil. Deforested areas are usually replaced by a succession of stages of forest degradation (light, medium, and heavy) to finally into completely degraded areas. The clearcut is the ultimate stage of deforestation, in which the complete removal of vegetation occurs. Throughout the process of forest degradation, pastures represent an alternative use of the area, which can turn or not into agricultural areas. When the area no longer meets the economic interests of trade in timber, livestock, and crops, it is abandoned and changes, according to the environmental conditions, to secondary forest. Deforestation is, therefore, a dynamic and complex process that can take years (http://www.obt.inpe.br/deter/avaliacao/RelatorioMonitoramento.pdf).

The detection of various stages of deforestation through satellite imagery is not an easy task, because the early stages of forest degradation (cutting of the marketable tree species for timber – selective logging) are hard to monitor by using satellite observations. According to INPE data, it is difficult to identify the deforested area before about 50% of it has already been affected (http://www.obt.inpe.br/prodes/metodologia.pdf). In order to monitor the processes of intense clear cutting and the land degradation process of selective logging, INPE has established the PRODES (http://www.obt.inpe.br/prodes/index.html) and DETER (http://www.obt.inpe.br/deter) land cover change monitoring programs.

Another important and potentially deleterious threat to the Amazon ecosystem caused by increased rates of deforestation and selective logging is the increase of fire occurrence. In fact, the clearing of forests and forest impoverishment through logging promote the increased occurrence of fire through the supply of flammable material (dry litter and soil) and the increase in edge areas (interface between forested and nonforested areas), which are more vulnerable to dryness and spread of fire (Laurance et al. 1998; Cochrane and Schulze 1999; Nepstad et al. 1999; Alencar et al. 2004; Barlow and Peres 2004). In addition, degraded forest increases the exposure of the lower layers of the canopy and litter to radiation and increased temperature, increasing their flammability (Aragão et al. 2007).

Under natural conditions of high precipitation index and high atmospheric moisture, the spontaneous occurrence of fire in the Amazon forest is relatively rare. Thus, most species of the forest are not adapted to fire, which hinders their recovery after successive fires. Barlow and Peres (2008) show, after 9 years of field experiment, that changes in forest structure and composition occur in cascade after each event of fire occurrence, culminating in vegetation very similar to an impoverished secondary forest. In this type of vegetation, pioneer species of short life cycle prevail, leading to a significant impoverishment of the environmental services provided by the forest.

Beyond the direct influence on the Amazon ecosystem, deforestation can affect the vegetation through changes in the regional climate. Modeling studies suggest a decrease in the evapotranspiration rates and an increase in atmospheric temperature caused by the large-scale replacement of forest by pasture (Nobre et al. 1991; Sampaio et al. 2007; Costa et al. 2007). It is estimated that these changes will lead to changes in local rainfall patterns, but how big exactly these changes will be is still uncertain. Small-scale deforestation can lead to an increase in local precipitation by the so-called 'wind-effect' (Roy and Avissar 2002; da Silva et al. 2008). On the other hand, large-scale deforestation may act to decrease the precipitation rate. Wang et al. (2009) observed increases in nonprecipitating clouds and decreases in the dry season precipitation over deforested areas in Amazonia. Modeling studies simulating the rainforest replacement by pasture also showed a decrease in rainfall with an increase in deforested areas (Nobre et al. 1991; Sampaio et al. 2007; Costa et al. 2007), with greater effects occurring for deforested area above 40% (Sampaio et al. 2007). In case of decreased rainfall and increased temperature, these local changes can exacerbate the potentially deleterious effects of climate on the Amazon region, described in the following sections.

2.15.3 Climate

Climate change resulting from increased emissions of GHGs, and from other human climate forcing, has the potential to increase the air temperature and related changes in precipitation patterns. Given the sensitivity of tropical forests to these variables, alterations in weather patterns, if pronounced, may result in significant changes in ecosystems and their ecosystems services. On the other hand, changes toward an ecosystem with less biomass can feedback to the climate response, accelerating the process.

Despite the importance of understanding how climate affects the structure and functioning of the tropical forest as we know it today, it has not been an easy task to identify current and plausible future changes in atmospheric variables in these regions. For the Amazonian forest, this is due in part to the scarcity of historical data and, in part, to the natural variability of precipitation (Marengo 2009).

Victoria et al. (1998) identified, based on data from 17 meteorological stations with long records for the period 1913–95, an increase in the air temperature of 0.56 °C century^{-1} with more pronounced variations in late 1960s and early 1970s. This value is similar to the value of 0.57 °C century^{-1}, found by Jones (1994) for South America, and was hypothesized as being mostly caused by increases in anthropogenic emissions of greenhouse gases for the early part of the record. Malhi and Wright (2004), based on data from CRU (CRU Global Climate Dataset, New et al. 1999), identified a much more pronounced increase in the rate of increase in temperature of tropical forests in general, the order of 0.25 °C decade^{-1}. This increase is more pronounced from the 1970s and was attributed by the authors to the global temperature increase caused by greenhouse gases emissions.

It is still more difficult to detect changes in the Amazon precipitation levels for the past and present century. Malhi and Wright (2004) did not record any significant trend of change for the Amazon. Marengo (2004, 2009) studied the 1929–98 period and suggested that there was no significant trend for the entire Amazon, but a slightly negative trend in the north and slightly positive in the south. Li et al. (2008), on the other hand, identified a negative trend in southern Amazon, for the period 1970–99. However, this trend so far has been related to decadal and multidecadal oscillations – natural features of the climate in the Amazon – rather than to an average increase of dry conditions in Amazonia (Marengo 2004, 2009; Marengo et al. 2011a,b; among others).

In terms of predictions, the models used by IPCC are more coherent among themselves in terms of their prediction of temperature increase (between 1.8 and 5.1 °C, under medium scenarios of increased emissions; Christensen et al. 2007) than in terms of changes in the rainfall pattern. Whereas some models project trends in the reduction of rainfall in the Amazon, other models project increases (Li et al. 2006). However, the average of all models simulates reduced rainfall during the dry season in the eastern Amazon and increased rainfall in the wet season in northern Amazonia (Salazar et al. 2007; Saatchi et al. 2007; Lapola et al. 2009; Malhi et al. 2008; Li et al. 2008).

2.15.3.1 Forest Response to the Climate

From the moment that there was an increased awareness that climate conditions like El Niño events could become more frequent or more intense in the future and that the prospects of deforestation associated with climate change could make the Amazon region drier and warmer, modeling experiments and in situ experiments began to simulate the response of forest to these expected conditions.

2.15.3.1.1 Amazon Dieback

One of the first models to include the response of the forest to the changes in climate conditions was the Hadley Center model. According to these model predictions, the annual rates of Amazon rainfall would vary from the current 4.56 to 1.64 mm day^{-1} in 2100, accounting for around 65% reduction (Cox et al. 2000, 2004). Under conditions of increased temperature and decreased precipitation, the Amazon region would suffer, by 2050, a major collapse (the so-called Amazon forest dieback), passing of the condition of slightly carbon sink of around 0.6 PgC year^{-1} (Malhi et al. 2006) to a strong carbon source to the atmosphere – the Amazon forest stores today as much as 90–120 PgC (Malhi et al. 2006; Saatchi et al. 2007) – thus exerting a positive feedback on climate.

2.15.3.1.2 Rainfall Exclusion Experiments

The expected decrease in rainfall in the Amazon forest has also led to field experiments of rainfall exclusion. These are complex field experiments of suppression of throughfall performed in the Tapajós National Forest, east-central Amazonia (Nepstad et al. 2002, 2007; Brando et al. 2008; Markewitz et al. 2010), and Caxiuanã National Forest, the eastern Amazon region (Fisher et al. 2007; Meir et al. 2008), both in Pará State.

The Tapajós experiment showed that the forest starts to increase mortality rates only after about 2.5 years of the induced drought. Concurrently, the rate of litter production only began to show an increase from the third year of dry season throughfall exclusion, in response to water deficit. Lianas, taller trees (overstory canopy) and larger trees (>30 cm diameter at breast height (dbh)), were the more sensitive species to the long-term drought (Nepstad et al. 2007). Wood production is the most sensitive component of living biomass to drought, declining 13% in the first year of exclusion to more than 62% in the subsequent period (Brando et al. 2008). The water uptake by deep roots is the most effective mechanism by which the forest supports, for some period, the decrease in precipitation. At the Tapajós rainfall exclusion experiment, the water uptake by the deeper roots was maintained for a period of about 2 years, showing a sharp decline thereafter Markewitz et al. (2010).

In Caxiuanã, the throughfall suppression was done throughout the year, not only during the dry season (Fisher et al. 2007) as it was in the Tapajós experiment. Unlike the results obtained by Nepstad et al. (2007), the Caxiuanã experiment showed a sharp decline in transpiration during the dry season, caused by the limitation of water transport in the soil-roots in the first year of exclusion. The results suggested that the forest is not able to support a 50% reduction in rainfall over the period of 1–2 years without an impact on the canopy and carbon exchanges. According to Fisher et al. (2007), one of the main differences between the experiments that could have led to different results in terms of forest response to drought was the fact that, in Tapajós, the soil layer was clayey and approximately homogeneous to about 90 m depth. Caxiuanã had a lateritic soil layer of about 4.5 m, which acts as a possible impending layer to the development of deep roots. The vertical extension of the root system and ability to retain water in the soil may therefore have increased the resilience of the forest drought experiment in Tapajós.

2.15.3.1.3 Fire Occurrence

As stated earlier, high levels of atmospheric moisture and dense canopies made the Amazon forest historically resistant to fire. Presently, fire occurrence is located close to road networks and deforestation areas, and, therefore, strongly associated with land use (Cardoso et al. 2003; Cochrane and Barber 2009). Alterations in temperature and precipitation, if severe enough, would change this pattern, possibly changing the fire regime to a condition of greater frequency and severity. At the climate scale, changes toward higher flammability and presence of sources of ignition will favor the species composition that are adapted to and associated with fire occurrence, such as savannas and grasslands (Bond et al. 2005; Cardoso et al. 2008).

2.15.4 Climate Extreme Events and Forest Response

It has been widely recognized that one of the main effects of plausible future climate conditions is an increased frequency of extreme weather events (Bates et al. 2008). This is because of the fact that a warmer atmosphere is able to promote both increased evaporation/evapotranspiration and increased moisture retention in the atmosphere. A crucial feature of temperature increase and climate change is that the water cycle is directly related to climate. At the local level, an increase in atmospheric temperature also increases water evaporation on earth's surface and plant transpiration, thus increasing the atmospheric humidity, which, in turn, is responsible for rain formation. At global and regional levels, different rates of surface warming around the globe move large, cool or warm, dry or moist air masses, which interact with the local atmosphere, thus determining regional climate and, possibly, the severe weather events.

Changes in atmospheric circulation patterns may increase the likelihood of torrential rainfall in some regions and the likelihood of extreme droughts in the other ones (Bates et al. 2008). In general, when most rainfall occurs in the form of short-term torrential rains, surface fast runoff is favored, and less water is stored in the soil profile. This can exacerbate the impacts of dry weather, because during the dry season the river flow is mainly feed by the groundwater, which is replenished by the wet season rainfall (Negrón-Juarez et al. 2007).

Despite the importance of understanding and accurately predicting extreme weather events, global climate models are not yet able to predict them with reliability when run in a hindcast mode. This may be because extreme events of drought have been hypothesized as being related to an increase in surface temperature of the oceans. Thus, future efforts to forecast drought will require the ability of global models to predict changes in surface temperature of tropical oceans (Dai 2010).

For the Amazon region, the extreme events of drought and flood are strongly related to changes in surface temperature of the tropical Pacific (ENSO – El Niño-Southern Oscillation) and the tropical Atlantic (AMO – Atlantic Multidecadal Oscillation). It has been recognized in the literature that changes in surface temperatures of the tropical Pacific Ocean (ENSO) have more influence on the wet season rainfall, while changes in surface temperatures of the tropical Atlantic Ocean have more influence on the duration and intensity of dry season rainfall in the Amazon (e.g., Li et al. 2006; Harris et al. 2008). When the warm waters of the tropical Pacific Ocean (El Niño) precede the anomalous warming of sea surface temperatures (SSTs) of the Atlantic Ocean, it may configure the worst possible climatological/hydrological condition, with interference in the regime of the Amazon river discharge and a range of impacts in the region, as pointed out in various parts of this chapter. The combination of these two climatic features causes a significant reduction of flow in the dry season, as recorded in the drought of 2010 (Marengo et al. 2011a,b).

The connection between the increase in the concentration of greenhouse gases and the increased frequency of El Niño events is still unclear (Yeh et al. 2009). On the other hand, major advances have been made in understanding the connection between the increase in the emission of greenhouse gases and the increase in surface temperatures of the Pacific Ocean (Wang and Dong 2010). According to Cox et al. (2008), the representation of the variation of SSTs in climatic global models caused by the increase of greenhouse gases coupled with the reduced pollution by aerosols in North America give evidence that droughts like the 2005 drought have, currently, a probability of occurrence of 1 in 20 years. However, this probability is hypothesized to increase to one in every two years by mid-century.

Although there are still difficulties to predict the occurrence of severe droughts in the Amazon, extreme events such as those that occurred in the past decades are increasingly better studied and explained in relation to their possible causes and consequences. For instance, the droughts of 1982/83, 1986/87, and 1997/98 (Marengo 1992; Uvo et al. 1998; Ronchail et al. 2002; Marengo 2004) were related to El Niño events of different intensities. Droughts of 1963, 2005, and 2010 were related to the anomalous warming of surface temperatures of the Atlantic Ocean (Marengo et al. 2008a,b; Marengo et al. 2011a,b), but Zeng et al. (2008) have raised the possibility of occurrence of 2002–03 El Niño associated to 2005 drought and Marengo et al. (2011a,b) have identified the occurrence of El Niño-associated 2010 drought.

In case of increased frequency of climate extreme events, it is necessary to take into account the possibility of an increased occurrence of floods in the Amazon. In 2009, the Amazon Basin experienced a flood of magnitude and duration seldom seen in decades. According to Marengo et al. (2011a,b), the rainy season in northern and northwestern regions began in early 2008–09 and was followed by a longer rainy season than normal. This caused the Negro River, the largest tributary of the Amazon, to reach a 107-year record.

2.15.4.1 Forest Response to the Severe Droughts

Before the 2005 Amazon drought, decreasing rainfall in the Amazonia basin had been mainly related to El Niño events, such as the 1982/83, 1986/87, and 1997/98 droughts (Marengo 1992; Uvo et al. 1998; Ronchail et al. 2002; Marengo 2004). The 2005 drought, because of its high intensity, not being associated to an El Niño event, and reaching different areas of basin than the areas normally affected by the El Niño events, was rather a typical and set out new directions of scientific research on climate in the Amazonia region. The drought of 2010 was even more intense than the 2005 drought. According to Lewis et al. (2011), whereas the 2005 drought affected about 1.9 million km^2 of forest, the drought of 2010 affected some 3.0 million km^2.

Unlike what usually occurs with severe drought events resulting from El Niño, the 2005 and 2010 droughts were particularly severe in the Amazon during the dry season, mainly impacting the southern and southwestern Amazonia rather than the northern and eastern regions, commonly affected during El Niño events (Marengo et al. 2008a,b; Zeng et al. 2008; Tomasella et al. 2010; Marengo et al. 2011a,b).

With regards to impacts, there are several studies evaluating the response of forests to drought. At the beginning of the observational research in understanding the Amazon forest as a whole, under the LBA (Large Scale Biosphere-Atmosphere Program – www.lba.inpa.gov.br) several studies have pointed to the fact that evapotranspiration showed an increase in the dry season compared with the values observed in the wet season. The explanation for this behavior was the fact that in the absence of water stress, the dry season had higher evaporative demand (higher solar radiation, higher temperature, less cloud cover, etc.) with consequent increases in photosynthesis. Among the relevant research on this subject we mention the pioneering work of Shuttleworth (1988), followed by the work of Sommer et al. (2002), da Rocha et al. (2004, 2009), von Randow et al. (2004), Souza-Filho et al. (2005), among others. Negrón-Juarez et al. (2007), based on results from experimental sites, report data on precipitation in the range of 3.8–4.3 mm day^{-1} in the dry season and values in the range of 2.5–4.1 mm day^{-1} in the wet season.

The notion that the Amazon rainforest could be resilient to short-term drought probably led to the conclusion, based on remote sensing data, that during the 2005 drought the Amazon forest would have displayed a 'greenness' (Saleska et al. 2007). However, later studies based on field data showed that an extreme event such as 2005 drought has led to the mortality of some Amazon forest species – mainly those of rapid growth and lower density of biomass. This increase in mortality rate meant that in normal years, the forest tends to present itself as a sink for carbon, but in years of extreme drought such as 2005, the forest can act as carbon source for the atmosphere (Phillips et al. 2009).

In addition to increased mortality of the forest, the extreme events of drought can greatly increase the incidence of forest fire, as pointed out by studies conducted by Nepstad et al. (2004), Aragão et al. (2007), and Cardoso et al. (2007), among others.

Although there is a growing recognition that the Amazon rainforest may be adversely impacted by extreme droughts, major issues still need to be better understood. Among them, we mention: Would the impacts of drought be relatively homogeneous throughout the length of the Amazon rainforest? What is the influence that factors such as chemical and physical composition of the soil, water table depth, moisture retention characteristics, and type and composition of vegetation could exert on the response of forest to extreme drought? Are the drought effects irreversible? How strong is the phenomenon of hysteresis? These issues, along with aspects related to the forest resilience to droughts, have been the subject of intensive research by the scientific community.

2.15.5 Factors of Forest Resilience

The drivers of anthropogenic changes in the Amazon region give us the notion that the forest has been subject to growing threats, which can lead to a collapse of the ecosystem. However, we cannot fail to consider, in this scenario, that there are factors that can provide a certain degree of forest resilience, that is, the ability of the forest to maintain its integrity when subjected to disturbance (Holling 1973).

A key factor, historically noted as able to provide some forest resistance to drought, is the assimilation of water from deeper layers of soil through deep root systems (Nepstad et al. 1994; Hodnett et al. 1996). This ability has been recognized through field experiments over time and is reinforced by observations that there are regions of the Amazon forest that display evergreen leaves, even during the dry season, which normally lasts 3–5 months (Nepstad et al. 1994; Myneni et al. 2007). Additionally, the ability of forests to remove water from deeper layers was identified as being responsible for the initial forest resilience shown during the first years of rainfall exclusion in the Tapajós site. At the same time, a potential barrier to deeper penetration of roots may have reduced the resilience of the forest in the Caxiuanã experiment (Nepstad et al. 2007; Fisher et al. 2007; Markewitz et al. 2010).

An additional mechanism that is pointed out as able to provide forest resilience in the long term is the so-called 'CO_2 fertilization' effect. As a result of the increase of atmospheric carbon, the CO_2 fertilization effect decreases the net loss of biomass caused by increased droughts. Because the plant stomata needs to open less for assimilation of the same amount of CO_2, the plant loses less water through transpiration, increasing the efficiency of water use and being less sensitive to soil moisture loss (Lloyd and Farquhar 2008). However, it is still unclear whether the decrease of transpiration in large scale may have the potential to change the local precipitation.

Another problem arising from the CO_2 fertilization is, according to Phillips et al. (2009), the possibility that pioneer species such as lianas gain advantage of the increased CO_2 in the atmosphere. Whereas these fast-growing species have lower wood density, its competitive advantage there could cause a decrease in the amount of carbon stored in the forest.

The great extent and heterogeneity of the Amazon forest is another important point that needs to be taken into account when considering the threats to the rainforest. It cannot be expected for a region with spatial dimensions of the same order of magnitude as the European continent to homogeneously respond to the rainfall reductions, increasing droughts, and fires. According to Killeen and Solórzano (2008), for example, the northwestern region normally shows high rainfall rates resulting from the winds going upslope in the Andes mountain ranges (Nilo and Nobre 1991), and thus would be less susceptible to critical levels of precipitation.

Another important aspect that might confer some degree of forest resilience to extreme events of drought is the existence of a well-pronounced seasonality between periods of drought and flood in lowlands and between dry and wet seasons in the areas of land in the region. The elevation of groundwater level during the wet season feeds the water table, which, associated with the soil water retention properties, is responsible for the maintenance of soil moisture that feeds the deep roots during the dry season. According to Negron-Juarez et al. (2009), it is the rain of the wet season that provides much of the groundwater accessed through the forest during the dry season. In the same sense, flood events, despite the deleterious impact they may cause on the riverine community and eventually on the forest response (anoxic conditions associated with high levels of water can promote tree mortality) have the potential to recharge the underground water reserves.

2.15.6 Changes in the Equilibrium State – Savannization

According to Scheffer and Carpenter (2003), abrupt changes could occur in some ecosystems and the theory suggests that the occurrence of these changes is due to the fact that there is more than one stable equilibrium state for this ecosystem.

This implies that gradual changes in temperature or other environmental factors may have little effect on the ecosystem until a threshold is reached. From this threshold, abrupt changes difficult to reverse occur. The possibility of more than one steady state to the Amazon region has been identified by scientific research for over three decades. From the moment in which scenarios of large-scale deforestation began to point to the possibility of an Amazonian rainforest climate more similar to a savanna region, possible changes in vegetation began to be investigated (Nobre et al. 1991). Then, with the prospect of a plausible future drying of the Amazon, these studies have intensified (Oyama and Nobre 2003; Scholze et al. 2006; Salazar et al. 2007; Vizy and Cook 2007; Lapola et al. 2009).

Oyama and Nobre (2003) found the existence of multiple stable equilibrium states in tropical South America in the current climate conditions and a set of plausible future climate conditions for a global atmospheric circulation model (CPTEC/COLA AGCM) coupled to a vegetation model potential (CPTEC-PVM). Two stable equilibrium states were found. One corresponds to the current distribution of Amazon forest and savanna biomes. The second corresponds to a new equilibrium state, in which forests are replaced by savannas mainly in the eastern region. Scholze et al. (2006) quantified the risk of forest loss as a result of climate effects. Thus, a dynamic vegetation model (LPJ-DGVM) was forced with 52 scenarios and 16 climate models, mapping the natural variability of fire frequency and supply of freshwater. The authors grouped the responses of ecosystems to warming simulated amounts of less than 2 °C, 2–3 °C, and more than 3 °C. The Amazon region is included among the regions that show increased risk of forest loss, with related increased savanna area and frequency of fire.

Salazar et al. (2007) studied the consequences of plausible climate scenarios on the distribution of biomes in South America in the twenty-first century by forcing a potential vegetation model with climate scenarios from 15 IPCC models, considering two IPCC emission scenarios (A2 and B1). In both scenarios, the results indicate a reduction in tropical forests and an increase in the region covered by savannas. The decrease in the area of rainforest in South America is 18% for the period 2090–99 for the A2 scenario (worst case). The regions of the tropical forest reduction are mainly concentrated in the southeastern Amazon. These changes were attributed by the authors to a decrease in soil moisture and/or an increase in the dry season. Cook and Vizy (2006) forced a model of potential vegetation (CPTEC/PVM) with results of a regional climate model grid of 60 km (MM5-MRS) to study the implications of climate projected for the twenty-first century (IPCC AR4 CCCMA) on vegetation of tropical and subtropical South America. The scenario of future climate is simulated using the increase of levels of atmospheric CO_2 to 757 ppmv. The coupled regional climate model predicts a 70% reduction in the extent of rainforest in the late twenty-first century and an expansion of savanna in the northeast. Lapola et al. (2009) investigated the distribution of rainforest and savanna biomes of South America using climate projections and a series of estimates of the increase in atmospheric CO_2 concentration. These authors concluded that, if the CO_2 fertilization effect in fact occurs and is maintained for a long time, it would be able to avoid changes of biome in most climate scenarios, even if the CO_2 fertilization effect is halved. However, regardless of whether fertilization effect is considered or not, if in the future the dry season is longer than 4 months, then a replacement of tropical forest by a less productive biome such as forms of tropical savanna is expected.

The sequence of change of stability of the Amazon forest and savanna biomes is illustrated in Figure 3. Figure 3a shows the steady state of the tropical rainforest, as it is today. Figure 3b shows the possibility of a second state of equilibrium – the occurrence of savanna forced by large-scale deforestation and climate. Figure 3c shows that the increased occurrence of fire associated with a greater frequency of extreme events of drought can enhance the stability of the condition of savanna, making it even more difficult for the condition of the Amazon forest to recover.

2.15.7 Synergistic Effect of Deforestation, Drought, and Fire – Are We Close to a Tipping Point?

The impacts of deforestation in the Amazon will most likely be exacerbated by the synergistic interactions between the local and regional climate including increased frequency of drought and fire occurrence. Studies have shown that large-scale deforestation can lead to an increase in temperature and decrease in evapotranspiration, with potential reduction in precipitation. Associated with deforestation, climate effects caused by GHG emissions emerge as an indirect threat to the Amazon ecosystem, acting, according to some models results, to further reduce the precipitation with concomitant increases in temperature. Most of the simulations projected decreases in rainfall during the dry season, especially in the eastern Amazon (Malhi et al. 2008). However, recent drought events that occurred in the Amazon in 2005 and 2010, associated with the warming of the tropical Atlantic Ocean, showed that western, southwestern, and southern Amazon are also subject to extreme seasonal drought (Marengo et al. 2008a,b; Tomasella et al. 2010; Lewis et al. 2011).

Under natural conditions (high rainfall, high atmospheric humidity, and high soil moisture) the Amazon forest is not sensitive to the occurrence of fire. However, this condition of low vulnerability to fire has been shown to be unstable in the face of numerous changes imposed by direct or indirect human actions: for example, loss of biomass associated with increased mortality in some species owing to the events of drought, increased edge effects, and forest degradation by logging; increased temperature; and decreased atmospheric humidity and soil moisture associated with soil management practices based on the use of fire. Increasing the incident radiation that penetrates through the canopy, increasing the temperature, drying litter, and providing more fuel for burning greatly increase the flammability of the forest.

Aragão et al. (2008) analyzed the interactions between rainfall, deforestation, and fires during the period 1998–05 in the Brazilian Amazon. The results showed that both deforestation and hot spots reach a maximum value during the dry season (June–September). The highest peak of deforestation was observed in May, whereas peaks of fire occurrence coincided with the months of less rainfall (August and September, in other words approximately 3 months after the rainy season reaches its peak deforestation). This is the time required for,

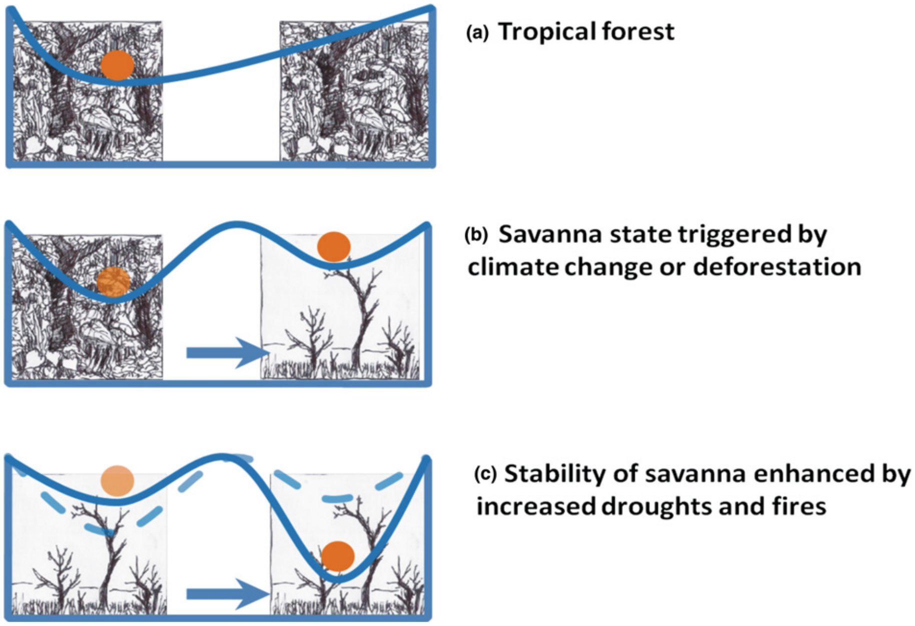
(a) Tropical forest
(b) Savanna state triggered by climate change or deforestation
(c) Stability of savanna enhanced by increased droughts and fires

Figure 3 Influence of the driving forces of deforestation, climate change, extreme events of drought, and fire on the bi-stability of the Amazon ecosystem.

later in the dry season, the wood to dry and be ready to be burned. At that time, the outbreak of fire reaches its maximum. Additionally, Aragão et al. observed that the cumulative number of outbreaks of fire was linearly related to the size of the area deforested annually for the period 1998–04. During the year 2005 because of drought, the number of hot spots increased by 43% compared to that expected for a similar area of deforestation ($\sim$19 000 km^2) in a normal year of drought.

A number of authors have raised the possibility of a tipping point for the Amazon (Scholze et al. 2006; Sampaio et al. 2007; Nepstad et al. 2008; Malhi et al. 2008; Nobre and Borma 2009). The review by Nobre and Borma (2009) presents a table with the main qualitative and quantitative results obtained so far, to identify potential tipping points for the Amazon ecosystem. The values that emerge from the use of different types of models that simulate the earth system are $T > 3\,^\circ C$ (Scholze et al. 2006; Salazar et al. 2007; Salazar and Nobre 2010) and deforestation area greater than 40% (Sampaio et al. 2007). However, these projections do not consider the occurrence of fire, which can greatly advance the prospect of collapse simulations based solely on changes in climatic conditions.

2.15.8 Conclusions

The analysis carried out in previous session leads to the conclusion that there may be limits to environmental drivers of change in the Amazon that should not be exceeded if one wants to maximize the likelihood of long-term survival of regional ecosystems and the local, regional, and global ecosystems services they provide to humankind. Therefore, it is important to examine the implications of the suggested thresholds in terms of climate and regional deforestation for Amazonian countries and international policies.

Let us start by the first limit on global warming, that is, $\Delta T_{\text{global warming}} < 3\,^\circ C$ (3.5 °C in the Amazon). Limiting global warming to less than 2 °C by early and sharp reductions of global emissions would put the system on safe ground because this is sufficiently far from the tipping point of 3.5 or 4 °C, although it does not guarantee that there will be no impact, especially on biodiversity. However, that reduction depends very little on Amazonian countries' policies, because global emissions arising from tropical land use change are only about 10% of global emissions (Global Carbon Project 2010).

The other threshold comes from land use change, that is, Total Deforested Area must remain less than 40% of the total basin area to increase the chances for forest permanence. This constraint clearly depends directly on Amazonian countries' policies for land use change and development. Policies to rapidly reduce deforestation (e.g., maintaining 80% of forests in rural landholdings as is with the current land use policy in Brazil) apparently have had a positive impact in the last 6 years.

In close association with land-use and -cover change, increases in fire occurrence represent other important driver of change in forests of Amazonia. Fires close to the edge of forests can extend the direct damage from deforestation further into pristine areas and enhance the likelihood of future burnings. In addition, because species in the tropical forests are not adapted to fire, additional burnings can lead to important changes in species distribution and composition.

Taken all together, deforestation, fires, and changes in climate and the frequency of its extreme events represent a set of drivers with strong potential for environmental changes in Amazonia. Considering them is essential in government actions for future land-use policy in the region. Even their isolated effects will likely have a high impact in the future of the region. Accounting for the synergy of their effects adds the perspective for changes that can be even faster.

The extent to which the combined effects of the major drivers of environmental change we discussed will lead to fast and perhaps irreversible changes in the ecosystems of Amazonia is an important subject of research. Although it makes sense that their synergistic effects are potentially catastrophic, factors of forest resilience such as resistance to drought or CO_2 fertilization can slow down these effects or prevent them. Concern on surpassing the forest's resilience levels, however, is still an important issue.

In order to maximize the likelihood of long-term survival of the ecosystems in Amazonia and the local, regional, and global ecosystems services they provide, important scientific questions should be addressed in the future, so new perspectives for land-use policy in the region can be considered. For example: What are the thresholds for irreversible changes in the region and how close are we from reaching these values? Are we considering all the major precursors of change related to anthropogenic activity in the region? In our view, considering all these questions only reinforces the need for environmental protection of the region.

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2.16 Blending Local Scale Information for Developing Agricultural Resilience in Ethiopia

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2.16.1 Introduction

Climate and humanity interact and feedback on a variety of scales. At a very local level, human actions release greenhouse gasses and aerosols. On a broader scale, the atmosphere mixes and integrates these pollutants, producing a spatially uniform, and rapidly increasing radiative forcing. Far from where this sequence began, the radiative forcing further warms the already very warm waters of the tropical Indian and western Pacific oceans. This warming, in turn, produces strong overturning climate anomalies that appear to be modifying the climate of eastern and southern Africa (**Figure 1**). At a very local level again, in eastern and southern Africa, some of the world's most vulnerable, poor, and food insecure populations experience changing climate means and variances, and begin to adapt their livelihoods to that new reality, sometimes in ways that ultimately strengthen this feedback loop of climate and adaptation. This interdisciplinary study focuses on the feedback between climate and adaptation, as represented by the interaction of climate, land cover/land use, and population growth in Ethiopia, one of the world's most food insecure countries.

To understand and inform agricultural adaptation to climate and variability in Ethiopia requires investigation across all of the multiple scales described above. Both 'bottom up' and 'top down' climate analysis approaches (**Figure 1**) must be combined with a temporally dynamic and area-specific understanding of Ethiopian population, land use, and livelihoods. Since 2005, our climate analyses have combined detailed evaluations of local rainfall trends with diagnostic analyses of large-scale climate evaluations. This work was prompted by the identification of a pattern of rainfall declines across densely populated, agriculturally important, and vulnerable areas of south-central and southern Ethiopia (Funk et al. 2002). A series of increasingly detailed diagnostic analyses have suggested, with increasing clarity and evidence, that these drying trends are tied to large, and at least partially anthropogenic, warming in the Indian Ocean and western Pacific (Funk et al. 2005; Verdin et al. 2005; Funk et al. 2008; Funk and Brown 2009; Williams and Funk 2011; Williams et al. 2011). The warm waters of the tropical Indian and western Pacific warm pool are very near to the thermal maxima that can be created by the interaction of radiative warming and local evaporation (Newell 1979), and closely track with global temperatures and anthropogenic radiative forcing. This warming has increased the rate of convection, rainfall, and diabatic heating in the Indo-Pacific warm pool, and helped trigger more frequent droughts across southern and south-central Ethiopia.

It is not only the magnitude but the location of these rainfall declines that has made them so important. Ethiopia's population is heavily concentrated in the south-central portion of the country. These food insecure populations typically practice rainfall-dependent agricultural, agro-pastoral, or pastoral livelihoods. Topography strongly modulates both the mean climate and the spatial livelihood patterns (**Figure 2**). Farm families typically occupy the cool highland regions receiving copious rains, while pastoralists live on the hot dry lowlands, and agro-pastoralists live in-between the two (Livelihoods Integration Unit 2010). Higher elevations receive more rainfall than low arid areas while supporting agricultural livelihoods and higher population densities. The population density of these areas dramatically varies (Livelihoods Integration Unit 2010), from over 300 people per km^2 in some parts of south central Ethiopia to less than 10 people per km^2 in areas dominated by pastoral livelihoods. Most rural people live in

http://dx.doi.org/10.1016/B978-0-12-384703-4.00234-3

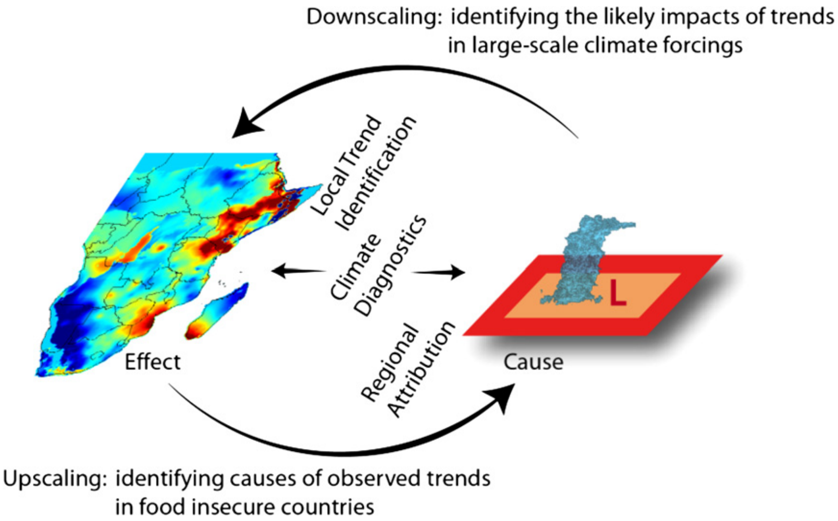
Downscaling: identifying the likely impacts of trends in large-scale climate forcings
Local Trend Identification
Climate Diagnostics
Regional Attribution
Effect
Cause
L
Upscaling: identifying causes of observed trends in food insecure countries

Figure 1 Schematic showing FEWS NET upscaling/downscaling approach to climate trend analysis. Shading on the left panel shows regression coefficients between main growing season rainfall and Indian Ocean rainfall (based on **Figure 7** from Funk and Brown, 2009). Red (blue) denotes a negative (positive) relationship. The right panel represents enhanced convection/rainfall/diabatic forcing over the Indian Ocean and Western Pacific.

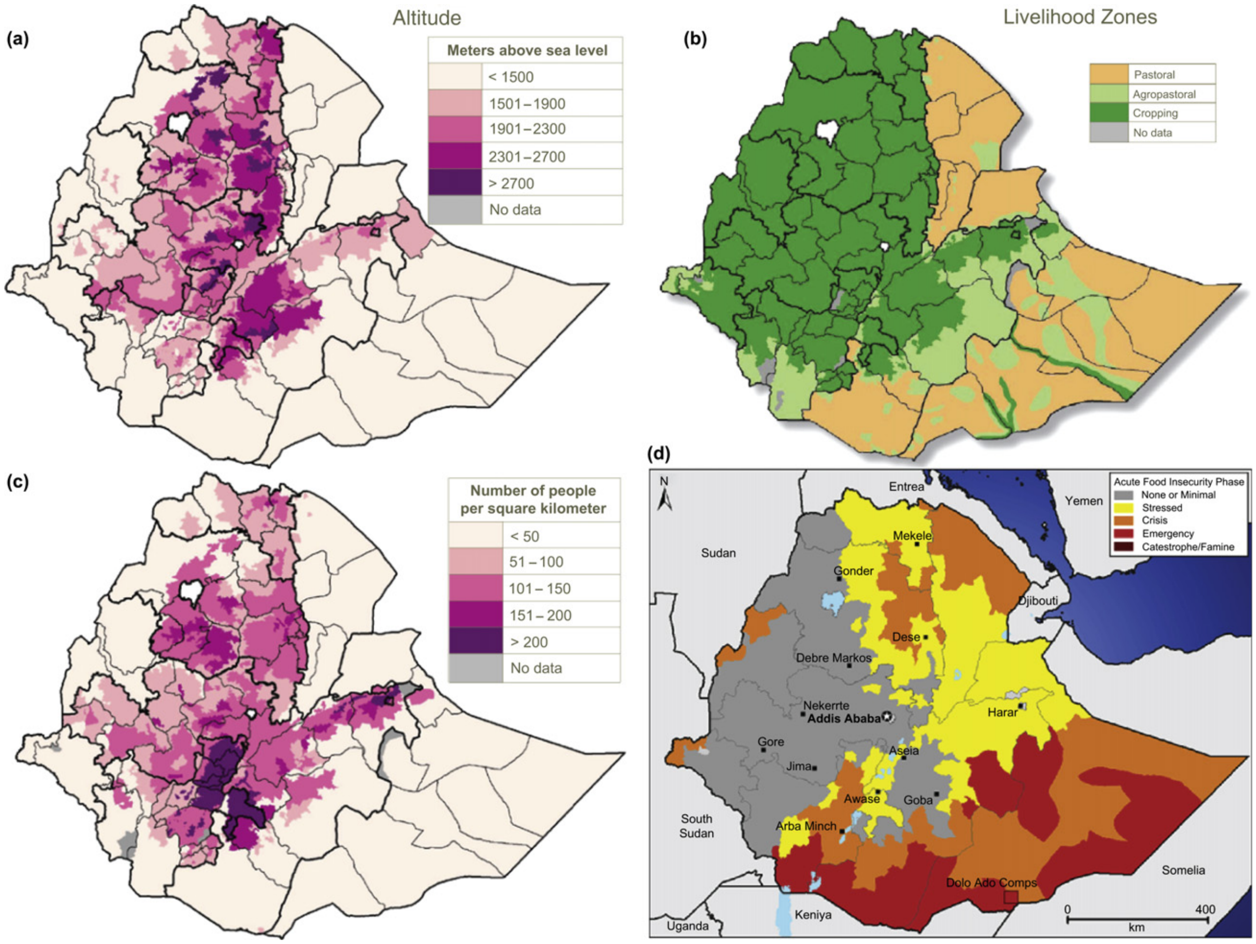
(a)
Altitude
Meters above sea level
< 1500
1501 – 1900
1901 – 2300
2301 – 2700
> 2700
No data
(b)
Livelihood Zones
Pastoral
Agropastoral
Cropping
No data
(c)
Number of people per square kilometer
< 50
51 – 100
101 – 150
151 – 200
> 200
No data
(d)
N
Acute Food Insecurity Phase
None or Minimal
Stressed
Crisis
Emergency
Catastrophe/Famine
Entrea
Yemen
Sudan
Mekele
Gonder
Djibouti
Dese
Debre Markos
Harar
Nekemte
Addis Ababa
Gore
Asela
Jima
Awasa
Goba
South Sudan
Arba Minch
Somelia
Dolo Ado Comps
0
400
km
Keniya
Uganda

Figure 2 Background information for Ethiopia: (a) elevation; (b) basic livelihood designations; (c) population density based on the 2007 National Population Census; a–c taken from the Livelihoods Atlas for Ethiopia (Livelihoods Integration Unit, 2010); and (d) the December 2011 Food Security Outlook for January–March 2012 from www.fews.net.

the highlands and middle-highlands, which comprise only one-third of the country, and this population tends to be primarily concentrated in the south-central portions of the country. The seasonality of rainfall varies in these areas. In the eastern Somali region, rains come twice a year – during the March–June *Belg* season and during the October–December *Deyr* season. In the south-central portion of the country, most areas receive both *Belg* and summer (June–September) *Kiremt* rains. Many farmers plant slowly maturing but high yielding 'long cycle' crops that mature across both the *Belg* and *Kiremt* seasons.

Population pressure plays an important role in Ethiopian food insecurity. In 2011, Ethiopia contained 90.9 million people (CIA 2011) and had a population growth rate of 3.2% (a doubling time of 22 years). Preplanned assistance provided by the Productive Safety Net Program supported some 7.4 million people, while an additional 4.5 million people required emergency humanitarian assistance due to poor rains and extremely high food prices (FEWS NET 2011). These 4.5 million people tended to be located in the south-central, southeastern, or eastern part of the country. Approximately 65% of these at-risk households primarily relied on agricultural livelihoods; the remainder were pastoralists or agro-pastoralists. In 2010, the country received by far the lion's share of World Food Program aid (24%), followed by 13% for Pakistan and 8% for Sudan. In 2011, Ethiopia faced the results of terrible rain deficits in the boreal winter and spring, and the resultant massive food emergency required an even greater expenditure of food aid.

As Ethiopia's population has grown, the land under cultivation has rapidly expanded (Funk et al. 2008). Important issues involve how these land cover transitions interact with local alterations of climate and whether these patterns of agricultural expansion could make Ethiopia more or less food secure in the near future. This study combines an evaluation of local climate trends and land cover change to briefly address these questions.

2.16.2 Methods and Data

This study uses three data sets: the Famine Early Warning System Network Trend Analysis (FTA) (Funk et al. 2011), Collection 5 land cover classifications (Friedl et al. 2010) derived from National Aeronautic and Space Agency's (NASA) Moderate resolution imaging spectrometer (MODIS), and the 2008 Landscan gridded population data set (ORNL 2011). These datasets provide detailed information about climate, land use, and population on a local scale. Our focus here is on making an interdisciplinary, nonquantitative evaluation of their joint spatial distribution and temporal tendencies. We do not address, except in passing, the underlying causes of the observed trends; our focus here is on their potential interaction as an example of effect of multiple vulnerabilities of Ethiopian agriculture. We do assume, however, that the large scale climate or socioeconomic or demographic drivers are such that the trends are likely to persist for the next 10–20 years. We acknowledge the uncertainty of such an assumption, but feel it is warranted because the local climate trends appear linked to slowly varying, at least partially anthropogenic, climate variations in the Indo-Pacific and because the population and land cover changes are tied to patterns of demographic or social inertia.

2.16.2.1 The FTA

To map the local mean and velocity of Ethiopian rainfall patterns, this study uses the FTA. The FTA fields (Funk et al. 2011) use satellite mean fields and environmental predictors (Table 1) to guide the spatial interpolation of station data to create a large number of point estimates of long-term means and decadal trends. The approach involves exploratory analysis and selection of a relatively small number (typically four to six) of predictors and the identification of a characteristic scale primarily determined by station density. Core to the FTA model-fitting are the local spatial correlations between station data and satellite and environmental predictors. At a local scale, satellite fields typically exhibit a strong spatial covariance with in situ observations, and this can be used to make accurate long-term mean and trend maps. Satellite fields also typically exhibit local spatial correlations that are much stronger and more consistent than physiographic fields. The local slopes of mean satellite-based rainfall estimates are better related to the true slope than indirect proxy indicators, such as the terrain elevation or slope.

The methodology was developed using a multivariate set of predictors including physiographic variables (elevation and slope) from the GTOPO30 data set, satellite observations of rainfall (RFE2, Xie and Arkin 1997), infrared brightness temperatures (Janowiak et al. 2001), and MODIS Land Surface Temperatures (Wan and Dozier 1989). The first step used moving window regressions to create a 'first cut' estimate of the gridded field, estimated at each target grid cell (i.e., each 0.1° cell across the maps). Each station value was then paired with the closest grid cell, and the regression model errors (residuals) were estimated. A model of the spatial structure of these errors was then used to produce another grid of values. Because the model of the spatial structure explicitly quantifies the spatial decorrelation with increasing distance, the interpolation produces spatial maps of standard error, contingent on the spatial distribution of the observation network. The moving window regression and residual fields were summed, creating an estimate that combines correlated exogenous predictors and the spatial covariance of the *in situ* observations. At each grid location, the final estimate combines the local regression estimate with the interpolated residuals.

Table 1 Climate data modeling products

Satellite observations	*Time period*	*Source*
MODIS land surface temperatures [°C]	2003–09	NASA
Meteosat infrared brightness temperatures [°C]	2001–09	NOAA/CPC
Merged rainfall estimates versus 2 [mm]	2001–09	NOAA/CPC
Physiographic predictors		
Latitude [°]	N/A	N/A
Longitude [°]	N/A	N/A
Elevation [m]	N/A	USGS GTOPO30

One advantage of the approach taken here, which calculates at-station changes and then interpolates the results, is that it supports the explicit estimation of interpolation errors. This allows us to address the following question: Does the density of the observed station network truly support the mapped trends? This degree of certainty can be represented as 'sigma fields,' calculated by dividing the interpolated trends by the interpolation standard errors; these provide a means of visualizing the statistical significance of the observed climate trends, vis–à–vis the spatial uncertainty field. The results presented here are supported by a dense network of gauge observations, obtained from Ethiopia's national meteorological agency, and the downward trend magnitudes for southern Ethiopia are typically around five times greater than the associated standard errors.

The analysis presented here is based upon the rainfall trend and mean fields for Ethiopia's boreal spring (March–April–May–June, MAMJ) and boreal summer (June–July–August–September, JJAS). The MAMJ and JJAS rainfall trends are based on the difference between the 1960–89 and 1990–2009 means, calculated from the station data. The MAMJ and JJAS rainfall climatologies were based on the 1960–89 period. The rainfall trend background models were based on longitude, latitude, elevation, land surface temperature, and infrared brightness temperature data. The rainfall climatology background models were based on the same fields and mean RFE2 rainfall estimates.

2.16.2.2 Land Cover Change Analysis

In conjunction with rainfall trends, this study also examined changes in land cover, as represented by the NASA MODIS Collection 5 global land cover-type classification maps (Table 2). The 500-m annual MODIS Collection 5 land cover data set uses neural networks and decision trees in conjunction with multitemporal reflectance data, spatial textures, enhanced vegetation index data, snow cover, land surface data, and terrain elevation to produce global land cover classifications using several land cover schemes (Friedl et al. 2010). In this study, we used the International Geosphere Biosphere Program (IGBP) scheme, which includes 11 natural vegetation classes, 3 developed and mosaiced land classes, and 3 nonvegetated land classes (Table 1).

The forested classes of the IGBP categories were merged and smoothed using 5 × 5 moving windows and 3-year composites. One composite period corresponds to the beginning of the study period (2001–03). The second period corresponds to 2006–08. For each 500 m pixel, 75 land cover values (from the surrounding 25 pixels, for each of the 3 years) were examined, and the most frequent cover type was estimated. This approach was used to dampen the impacts of interannual climate variations and to focus on the large-scale patterns in land cover/land use change.

Pixels that transitioned from forest to crop or forest to mixed natural vegetation and crop between 2001–03 and 2006–08 were then identified and related to 14 predictors: elevation, slope, distance to rivers, tree cover %, maximum normalized difference vegetation index (NDVI), NDVI fragmentation, cover-type diversity, distance to cover-types, distance to roads, distance to villages, population density, mean annual temperature, mean annual rainfall, and precipitation of the driest month. A large number of forest-to-crop transitions were identified over south-central Ethiopia. To explore the drivers of these transitions, the transitions were modeled using logistic regression (LR). LR is a special case of multiple regression in which the dependent variable is discrete (Hosmer and Lemeshow 2000), such as land cover types. LR was used to assess which of the 14 independent variables were the most effective predictors of forest-to-crop and forest-to-mixed natural vegetation and cropland transitions.

Table 2 Initial IGBP land cover classes used in modeling cover changes in Ethiopia

Code	*Land cover*
0	Water
1	Evergreen needleleaf Forest
2	Evergreen broadleaf Forest
3	Deciduous needleleaf Forest
4	Deciduous broadleaf Forest
5	Mixed forest
6	Closed shrublands
7	Open shrublands
8	Woody savannas
9	Savannas
10	Grasslands
11	Permanent wetlands
12	Croplands
13	Urban and built-up
14	Cropland/natural vegetation mosaic
15	Snow and ice
16	Barren and sparsely vegetated
254	Unclassified

2008 LandScan population data (Dobson et al. 2003) provided a third input to our analysis. This 30 arc-second resolution population data set disaggregates subnational census data based on likelihood coefficients that are based on proximity to roads, slope, land cover, and other information. Coarser resolution, multiyear, Gridded Population of the World population estimates (CIESEN 2011) were used to assess population change over time. Crop statistics from the United Nations' Food and Agriculture Organization were also evaluated.

2.16.3 Results

2.16.3.1 Local Variations of Climate

Between the mid-1970s and late 2000s, *Belg* and *Kiremt* rainfall, based on quality-controlled station observations, decreased by 15–20% across parts of southern, southwestern, and southeastern Ethiopia. We have described these declines in two ways: as a contraction of the areas receiving adequate rainfall for viable agricultural livelihoods (assumed to be greater than 500 mm of rainfall per rainy season) and as a map of anticipated changes in rainfall and temperatures (assuming a persistence of patterns observed).

Ethiopia receives most of its rain between March and September. Rains begin in the south and central portions of the country during the *Belg* season, then progress northward, with central and northern Ethiopia receiving the most precipitation during the *Kiremt* season. Rainfall totals of more than 500 mm during these rainy seasons typically provide enough water for viable farming and pastoral pursuits.

While local alterations in climate can be interpreted in many meaningful ways, one simple, and powerful, approach is to look at changes in the ‘front lines’ of climate suitability; transition zones between areas that were, and soon may not be, viable for a given livelihood pattern. In Ethiopia, transitions between viable and nonviable cropping conditions align, approximately, with the 500 mm isohyets in seasonal rainfall totals. **Figure 3** shows these isohyets for the MAMJ and JJAS seasons for the 1960–89 average, the 1990–2009 average, and a 2025 projection. Note that this 2025 ‘projection’ combines 20 years of observed change (1990–2009) with 16 years of predicted changes, based on a persistence of recent trends (a linear extrapolation). This is the approach used for the scenario generation of plausible future local climate. The areas that appear likely to experience a contraction have been shaded to emphasize that they may be areas of emergent risk. These regions will likely experience a substantially higher frequency of droughts, subjecting households to the repetitive shocks that decrease resilience and help feed a spiral of poverty.

Between 1960 and 1989, the area receiving (on average) this much rain or more during the *Belg* season was large, over 215 000 km^2. For the *Belg* season, this area is shown in light brown in the upper left panel of **Figure 3** and should be understood to lie beneath the dark brown and orange areas. Over the past 20 years, the areas receiving sufficient *Belg* rains have contracted by 16% (dark brown polygon), exposing densely populated areas in the Rift Valley, in Southern Nations, Nationalities and People's Region, and Oromia, where agriculturalists face near-chronic food insecurity (see Objectives and Methods section below for location and population totals). A continued decline in rainfall could result in a contraction of the area receiving more than 500 mm during the *Belg* season (orange polygon) by another 16%. In the eastern highlands, future *Belg* rains appear threatened as well.

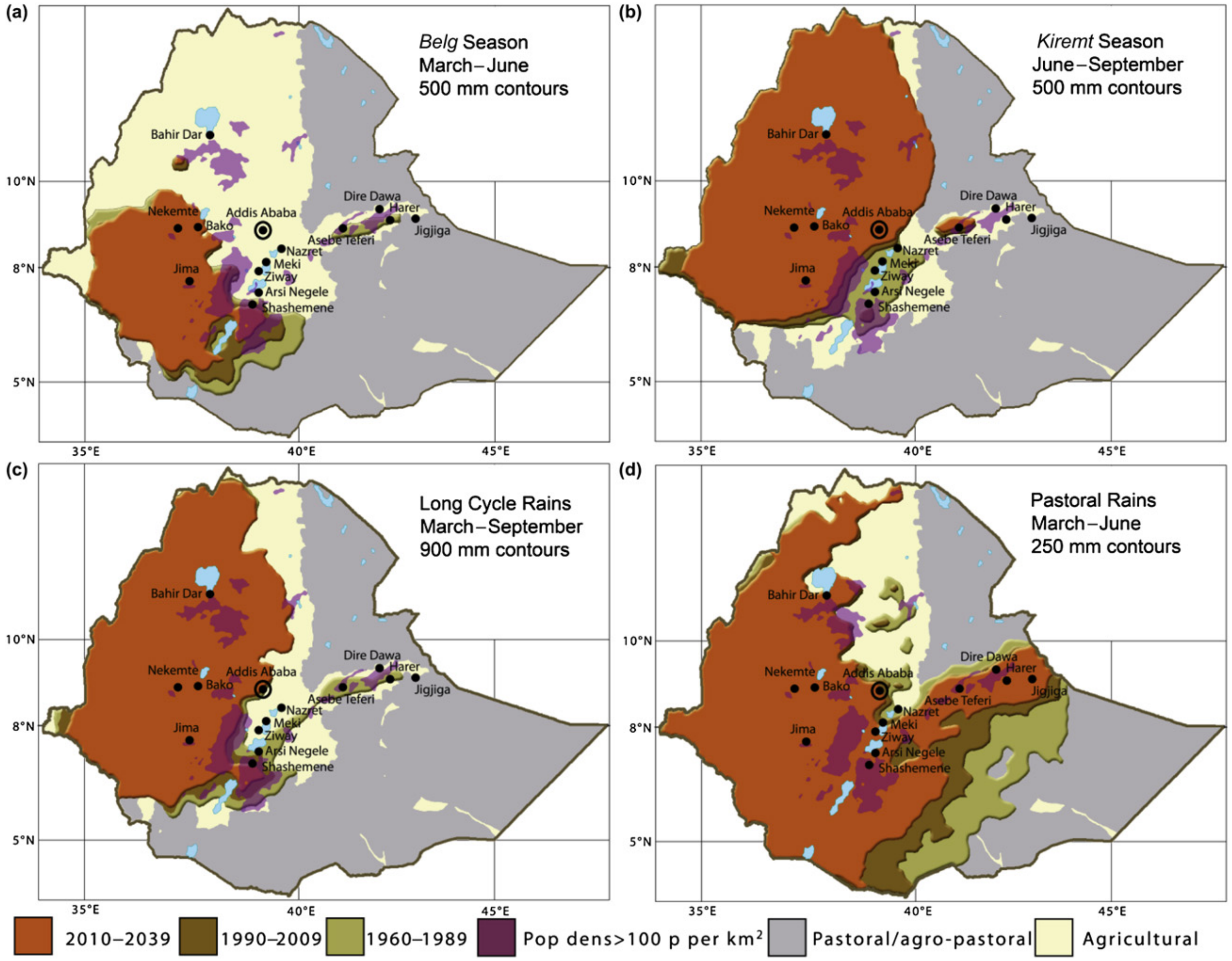
(a)
Belg Season
March–June
500 mm contours
(b)
Kiremt Season
June–September
500 mm contours
(c)
Long Cycle Rains
March–September
900 mm contours
(d)
Pastoral Rains
March–June
250 mm contours
Bahir Dar
Nekemte
Bako
Addis Ababa
Dire Dawa
Harer
Jigjiga
Asebe Teferi
Nazret
Meki
Ziway
Arsi Negele
Shashemene
Jima
10°N
8°N
5°N
35°E
40°E
45°E
2010–2039
1990–2009
1960–1989
Pop dens>100 p per km^2
Pastoral/agro-pastoral
Agricultural

Figure 3 Climate change in Ethiopia: (a) Average location of the March–June 500 mm rainfall isohyets for 1960–89 (light brown), 1990–2009 (dark brown), and 2010–39 (predicted, orange). (b) Average location of the June–September 500 mm rainfall isohyets. (c) Average location of the March–September 900 mm rainfall isohyets. (d) Average location of the March–June 250 mm rainfall isohyets. The semitransparent purple overlay shows the areas with 2007 population densities of greater than 100 people per km^2. The yellow shading in the background delineates agricultural areas; the gray background delineates agro-pastoral and pastoral livelihood areas (cf., **Figure 2(b)**).

These affected areas have approximately 16.6 million inhabitants (based on 2008 Landscan data).

During the *Kiremt* season, between 1960 and 1989, the area receiving (on average) more than 500 mm is shown in light brown in **Figure 3(b)**. Over the past 20 years, the areas receiving sufficient *Kiremt* rains has also contracted (dark brown polygon), exposing many of the same Rift Valley populations in SNNPR and southern and eastern parts of Oromia. These affected areas have approximately 12.6 million inhabitants (based on 2008 Landscan data).

March–September 900-mm rainfall accumulations, which directly relate to the performance of slow maturing 'long cycle' crops (**Figure 3(c)**), exhibit large areas of reductions in rainfall, running in a band that stretches from the eastern highlands to south-central Ethiopia. The 900 mm threshold was chosen because it coincides with the extent of long cycle cropping examined in previous FEWS NET studies. Approximately 20.7 million people live in these affected zones. Poor long cycle crop performance in the south-central and eastern midlands and highlands could directly affect the livelihoods of many of these people, while adding pressure to national cereal prices.

Figure 3(d) especially relates to climatic patterns observed in pastoral zones. It shows the northwestward retreat of the 250 mm *Belg* season March–June isohyets between 1960–89 and 1990–2009, and as projected forward for 2010–39. While the October–December *Deyr* rains have exhibited little trend (not shown), observed rainfall declines during the *Belg* season are reducing the quantity and quality of viable pasturelands. More frequent droughts in these areas are making it difficult for livestock to recover from poor rainy seasons. The area of contraction affects a total population of approximately 7 million. Note that even dryness in the *Belg* and *Kiremt* crop growing areas also impacts pastoralists and agro-pastoralists by contributing to higher cereal prices and leading to lower terms of trade when livestock are traded or sold for food.

2.16.3.2 Declining Rainfall in Densely Populated Areas

The purple areas in all panels of **Figure 3** highlight very high population densities; many of these most densely populated areas are affected by the described March–June, June–September, or March–September rainfall declines. The correspondence between the high population densities in the south-central Rift Valley area and the receding long-cycle (March–September) rainfall pattern is of particular concern. This area is heavily populated, all available fertile land has been cultivated, and the size of land holdings is diminishing as population grows. It appears likely that the combination of population growth, land degradation, and more frequent droughts will result in more frequent food-related crises.

2.16.3.3 Observed Changes in Rainfall and Temperature Projected Forward

Figure 4 projects the spatial patterns and quantities of future rainfall reductions and temperature increases by extending the rate of observed 1960–2009 changes for each season, through the 2010–39 period, based on an assumed persistence of the observed trends. For the *Belg* rains, rainfall declines range from −150 to −50 mm across the south-central and eastern portions of the country and will be associated with lower *Belg* harvests and poorer pastoral rangelands during the summer and early fall. This may be particularly disruptive for pastoralists and agro-pastoralists living in southern Oromia and western Somali regions who, at present, already rely upon meager *Belg* rains for their livelihoods. For the *Kiremt* rains, rainfall declines range from −150 to −50 mm across the western and southern portions of Ethiopia. The combined *Belg* and *Kiremt* rainfall reductions total a loss of more than 150 mm of rainfall per year in the most heavily populated **(Figure 2)** long cycle crop growing area of the country.

If recent warming trends continue, and they are very likely to, most of Ethiopia will experience more than a 1.0 °C increase in air temperature (**Figure 4(b)**, bottom) with the

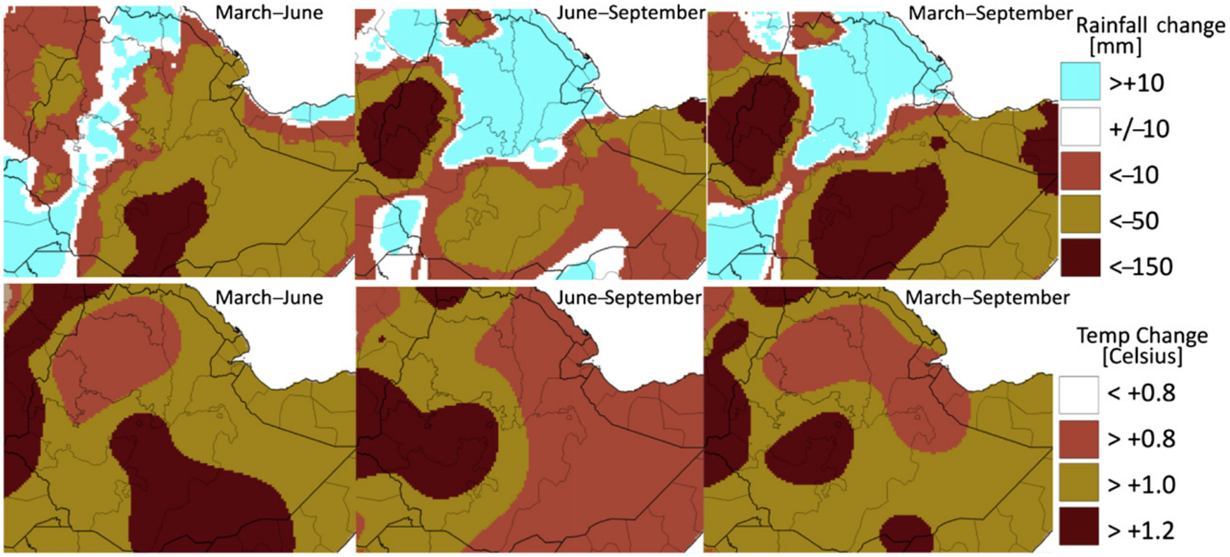

Figure 4 Observed and projected change in March–June, June–September, and March–September rainfall (top) and temperature (bottom).

warming tendency projected to be greatest in the south-central portion of the country. This warming will intensify the impacts of droughts and could particularly reduce the amount of productive cropland for coffee, since coffee plants typically prefer temperatures cooler than 22 °C.

The results in Figures 3 and 4 help us interpret the *local* climatic impacts, presuming, of course, persistence in the observed rates of rainfall decline. Unfortunately, the location of the retreating isohyets in Figure 3 tends to coincide with some of the most densely populated areas in Africa, with Landscan 2008 population densities of over 350 people per km^2. While estimating 'exposure' to climate variability is difficult, it seems likely that millions of people within the retreating contours will face recurrent food crises, as seems to have already been the case over the past decade (www.fews.net).

2.16.3.4 Land Cover Change Analysis

While the trends shown in Figure 4 and the retreating isohyets shown in Figure 3 are worrisome, it is important to recognize that there are vast areas of Ethiopia where the agro-climatic conditions have been stable or even improving. Ethiopia's steep topography and the associated steep climatological rainfall gradients provide a natural resistance to some climate variation. Even in dry years, most of north-central and north-western Ethiopia receives plentiful rainfall. The climatic security of these 'water towers' may be one reason that the country has such a long history of continuous settlement and government. It is also worth noting that the northern parts of the country have not exhibited the same downward trends as the south (Funk et al. 2011; Williams et al. 2011).

It is important to identify, therefore, *where* in Ethiopia agriculture is expanding. Different spatial patterns could have very different implications for future food security. Expansion in the climatically secure north might decrease interannual variation in national cereal production, increasing the country's agricultural resilience to climatic shocks. Expansion in the south might increase the year-to-year variance of crop yields and amplify Ethiopia's exposure to rainfall declines.

Are patterns of agricultural extensification located in the relatively secure central or north-western parts of the country? One answer to this question, as depicted by 2001–03 and 2006–08 MODIS Collection 5 land classifications, is shown in Figure 5. According to the MODIS Collection 5 classifications, most of the forest-to-crop transitions in Ethiopia have predominantly occurred in the south-central portions of the country, where population densities are high (Figure 2). For both the forest-to-crop, forest-to-mixed crop, and natural vegetation classes, the spatial pattern of transitions is heavily slanted toward the southern half of the country. These areas, in general, are associated with drying and warming trends (Figure 4) and retreating *Belg*, *Kiremt*, and long cycle contours (Figure 3).

We formalize these relationships by using logistic regression (Hosmer and Lemeshow 2000) to examine the predictive power of a set of 14 independent variables. While space limitations do not permit a full discussion of these results here, we note that the best predictors for these transitions were the distance to the closest village and population density. Average distance-to-closest-village distributions for four transition classes (barren to open vegetation, closed to open vegetation, forest to crop and forest to mixed crop, and natural vegetation) are shown in Figure 6. There is a clear tendency for transitions from forest-to-crop to occur near occupied areas and within regions with higher population densities. This proclivity, combined with demographic inertia of populations to continue to rapidly grow due to the large number of potential mothers present within the existing population (Bongaarts 1994), implies that most agricultural growth is likely to be coincident with areas that appear associated with drying tendencies.

2.16.3.5 Population Growth, Climate Gradients, and Future Food Security

Ethiopia's population of 90.9 million people expanded by 68% between 1990 and 2010 (or by 33 million people). According to Gridded Population of the World statistics (CIESEN 2011), most of these population increases occurred

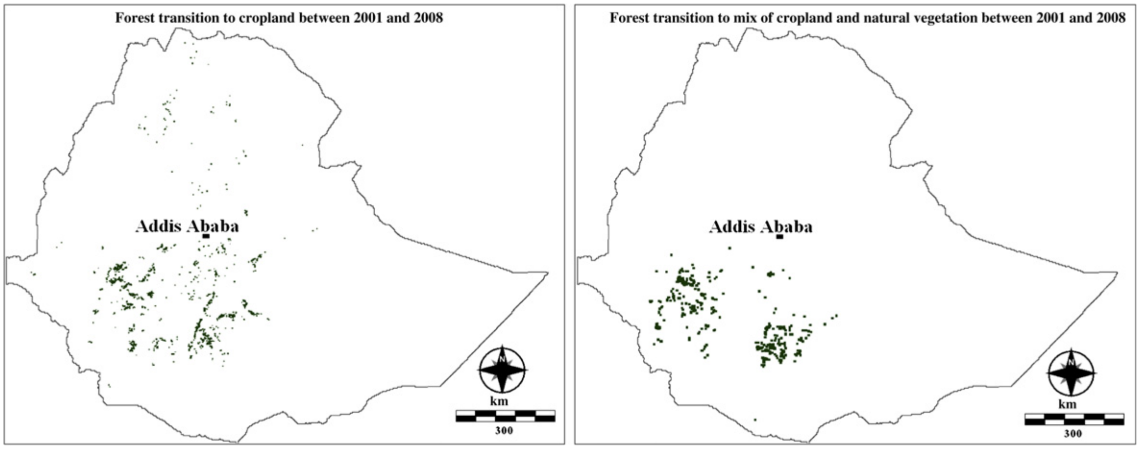
Forest transition to cropland between 2001 and 2008
Addis Ababa
km
300
Forest transition to mix of cropland and natural vegetation between 2001 and 2008
Addis Ababa
km
300

Figure 5 MODIS land cover transitions from forest to cropland (left) and land cover transitions from forest to mix of natural vegetation and cropland (right).

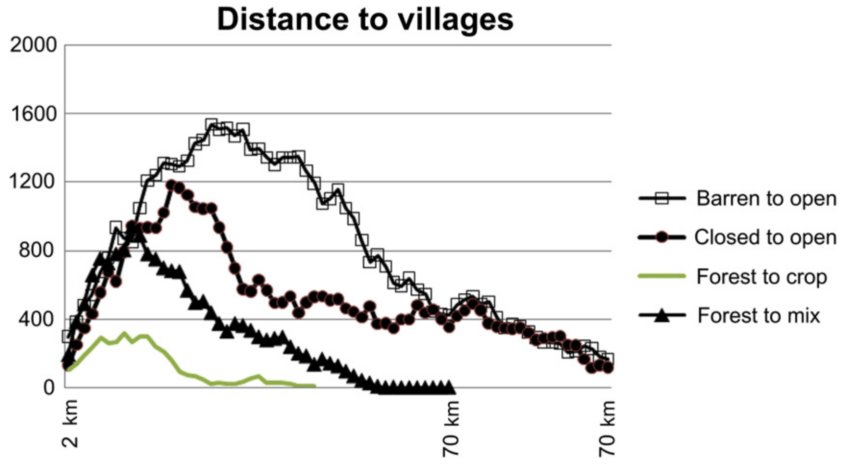

Figure 6 Distance to nearest village for various land cover transition classes.

in Oromia (+11 million people) and SNNPR (+6 million), densely populated areas where we have seen that rainfall has been rapidly declining (Figures 3 and 4), while the populations of chronically food insecure Somali, Tigray, and Afar regions have increased by ~1.5, 1.9, and 1.1 million people, respectively. Given that Ethiopia is a land-locked country that depends on rain-fed agricultural, agro-pastoral, and pastoral livelihoods, this population expansion will place increasing stress on limited natural resources. Crop statistics from the Food and Agriculture Organization of the United Nations show that per capita cereal production in Ethiopia is relatively low (150 kilograms per person per year). While yields have been improving, the amount of farmland per person has been declining at a rate twice as fast. If these trends persist, per capita cereal production could decline by 28% by 2025.

In order to meet its food needs and improve food security, Ethiopia will need to both improve its yields and continue expanding its agricultural area. Planning should take into account the relative security of the northwest and central highlands, where there are, and will be, large areas with low climatic crop risk. We can visualize the interaction of climate trends and Ethiopia's complex mean climate by examining transects of mean observed and projected rainfall. Figure 7 shows the observed 1960–89, observed 1990–2009, and projected 2010–39 June–September rainfall means at 8°N. This graphic indicates how the local climate can interact with terrain. In Ethiopia, rainfall tends to increase to the west and at higher elevations, and the interaction of these two features is seen in a rise, a decrease, and then another rise in rainfall when moving from east-to-west at 8°N. Population density in central Ethiopia tends to peak in the mountains and valleys of the

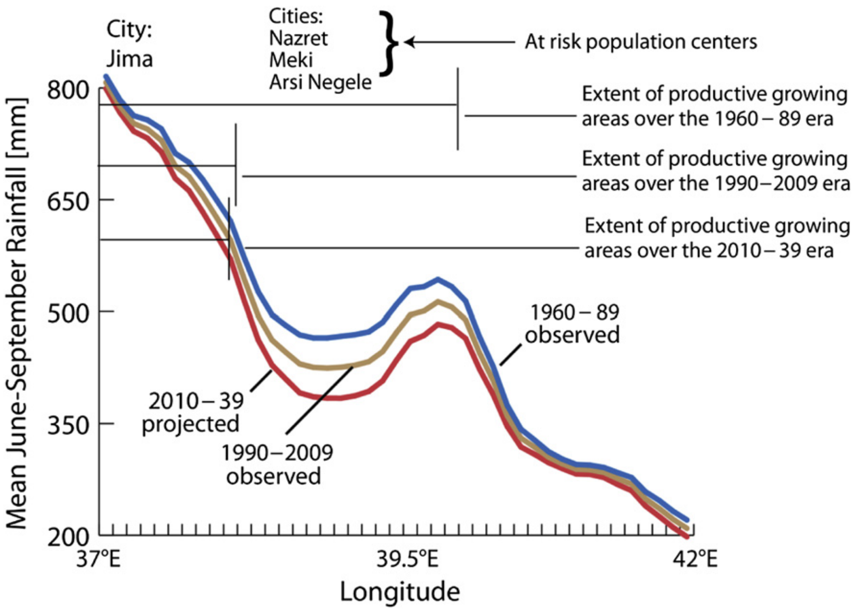

Figure 7 Transects of mean 1960–89 and 1990–2009 June–September rainfall, along with 2010–39 projected rainfall (transects taken along 8°N).

central Rift area. This area has already experienced substantial declines in *Kiremt* rains between 1960–89 and 1990–2009, and further declines seem likely. Population densities in this area (**Figure 2(c)**) are very high, and this area of Ethiopia appears to be an emergent area of increasing risk. In the areas surrounding cities like Nazret, Meki, and Arsi Negele, declining rainfall should be of great concern regarding the impacts it is having on the food security of these large populations (**Figure 3(b)**).

2.16.3.6 Livelihoods and Socioeconomic Analysis

Prior FEWS NET analysis by the Livelihoods Integration Unit (LIU 2010) provides a useful and interesting context for analyzing and discussing vulnerability patterns of climate and land use change. Drawing from extensive livelihood mapping surveys and Ethiopian socioeconomic data archives, the LIU has constructed a detailed Livelihoods Atlas. Of particular concern here is how the interaction of mean climate, climate variability, market access, road networks, and livelihoods shape the distribution of poverty and limit access to food and wages. As the Nobel Laureate and economist, Amatya Sen, pointed out in 1982, it is ultimately the limited access to food that creates famine (Sen, 1982). It is when food prices rise and food becomes too expensive that the poorest face starvation, malnutrition, and associated diseases. Such, for example, was the case in 2011, when marginalized and impoverished pastoralists in Ethiopia, Somalia, and Kenya faced rocketing food prices. We have also argued, however, that agricultural productivity, a major source of income, also plays an important role in food insecurity (Funk et al. 2008). A major determinant of household agricultural production is the amount of cultivated land per household (**Figure 8(a)**). Farm size plays an important role in determining the average food security of households, as measured in the average household income, expressed as a percentage of the annual household food needs (**Figure 8(b)**). Blue shades in this figure are used to map wealth within agricultural households; red shades are used to map pastoral wealth. There is a reasonable association between average household wealth and average farm size. Wealthier families tend to have more than two hectares of farmland. This does not appear to be the case in the south-central portion of the country (marked with a red box, 4–8°N, 37.75°–40°E),

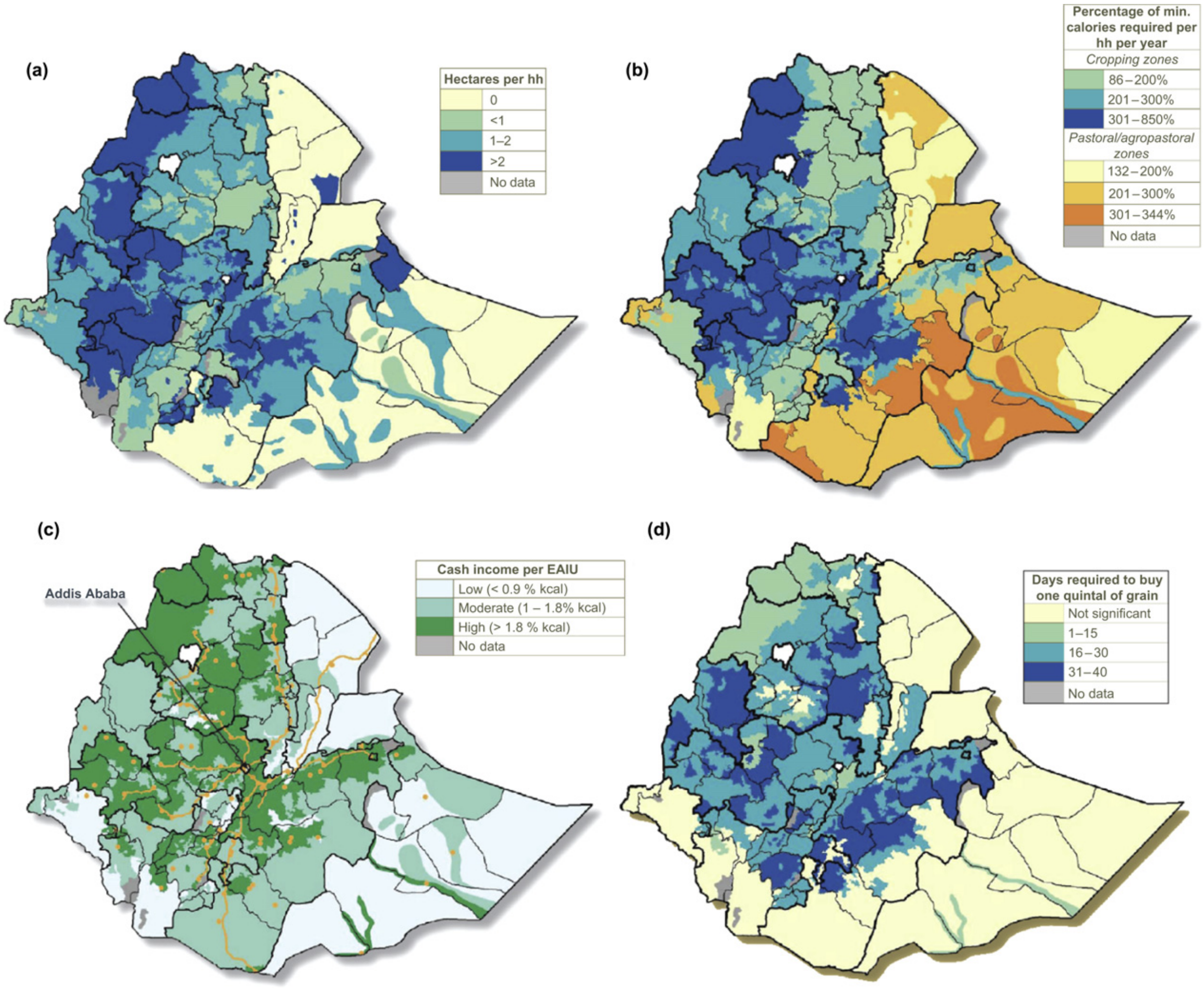
(a)
Hectares per hh
0
<1
1–2
>2
No data
(b)
Percentage of min. calories required per hh per year
Cropping zones
86–200%
201–300%
301–850%
Pastoral/agropastoral zones
132–200%
201–300%
301–344%
No data
(c)
Addis Ababa
Cash income per EAIU
Low (< 0.9 % kcal)
Moderate (1 – 1.8% kcal)
High (> 1.8 % kcal)
No data
(d)
Days required to buy one quintal of grain
Not significant
1–15
16–30
31–40
No data

Figure 8 Livelihood and socioeconomic information for Ethiopia. (a) Hectares of farmland per household. (b) Total income (food and cash) excluding aid by livelihood type of zone. (c) Cash income per Ethiopian Animal Income Unit. (d) Days of work required to buy one quintal of grain.

where we have noted substantial climate and land use changes. In this densely populated region (**Figure 1**) many households have less than one hectare per family of farmland and have typical incomes of less than 200% of their total family caloric needs. Small land holdings in poor climatic regions support chronic poverty. These fragile household food economies can be shattered by volatile food prices or failed rains.

Despite low access to markets, many households in south-central Ethiopia are nonetheless heavily dependent on purchased food (LIU 2010). The cost of food can be measured in terms of the cash income per Ethiopian Animal Income Unit (EAIU). This is a unit based upon an analysis of total income nationally derived from each species, EAIU calculation: 1 camel = 6 shoats; 1 cow/ox = 4 shoats. In the green areas of **Figure 8(c)**, demand is high, availability is low, and the relative cost of livestock is high. While some of these locations are associated with high incomes (**Figure 8(b)**), there are several regions where high food prices coincide with low incomes. South-central Ethiopia is one such region.

Labor can be another important source of revenue that alleviates food insecurity. **Figure 9(d)** shows the number of days of manual labor typically required to purchase a standard measure of grain in Ethiopia. The value of labor dramatically varies across the country. In some areas, "local workers may be many, the crop less valuable or labor-intensive, and grain expensive far from surplus markets" (LIU 2010). Wages in these regions, which are shown in deep blue in **Figure 8(d)** are "as low as they can be: the price of a day's food." Wages are typically very low across most of south-central Ethiopia.

Summarizing **Figure 8**, it appears that high vulnerability agricultural households in Ethiopia might be categorized as small land holdings (**Figure 8(a)**), low average total household incomes (**Figure 8(b)**), high average food prices (**Figure 8(c)**), and low average wages (**Figure 8(d)**). These problem areas are not limited to south-central Ethiopia and in fact many regions of north-central and north-eastern Ethiopia experience chronic and severe food insecurity. Nonetheless, the coincident expansion of agriculture and aridity across south-central Ethiopia appears likely to affect some very fragile food economies where the combined effects of poverty, high prices, and small farms sizes make development difficult.

2.16.4 Summary and Discussion

Our basic hypothesis is that East Africa is becoming drier due to an intensification of the climatological processes that make it dry to begin with. Gill (1980) showed that the tropical atmosphere forced by a steady source of diabatic heating produced an overturning circulation that resembled the observed Walker circulation. A stationary Rossby wave response to the west of the source of diabatic heating could increase subsidence over eastern Africa. While such a simple model masks the very complex factors that create East African weather, such behavior can be identified in both canonical correlation analyses of reanalysis fields and diabatic forcing modeling experiments that demonstrate a negative association between rainfall over the Indian Ocean and East Africa (Funk et al. 2008). More recent work has emphasized the joint warming of sea surface temperatures (SSTs) in both the Indian Ocean and western Pacific, suggesting that increases in Indo-Pacific Warm Pool convection can be understood as a spatial extension of the Warm Pool (Williams and Funk 2011). Williams and Funk (2012) emphasized the long-term trend in Warm Pool SSTs, rainfall, and winds, and the important interaction of this trend with interannual La Niña-like climate events. It has been recognized that an evaluation of trends plays an important part of early warning systems (Funk and Verdin 2009) and the new appreciation of La Niña's climate implications for the region helped trigger effective early warning of the 2011 East African food crisis (Ververs 2012; Funk, 2011). The more recent work of Lyon and Dewitt (2012) identified the exceptional warmth of the 1999–2011 period and used SST driven modeling experiments to demonstrate the important, and potentially dominant, role played by the western tropical Pacific. A recent evaluation of the new phase 5 coupled ocean–atmosphere model intercomparison project SST simulations (Funk 2012) prepared for the fifth Intergovernmental Panel on Climate Change assessment report indicates that this warming is almost perfectly predicted by the models solely driven with anthropogenic greenhouse gasses and aerosols, and exceptionally warm MAMJ SSTs ($\geq$28.7 °C) in the Indo-Western Pacific (15°S–15°N, 60°–170°E) have repeatedly occurred in the twenty first century (2001–2006, 2009–2012). It seems likely that western Pacific SSTs may dominate equatorial eastern Africa rainfall variations during boreal spring, while during boreal summer warming in the south-central Indian Ocean may tend to reduce rainfall across southwestern Ethiopia, southern Sudan, and northern Uganda (Williams et al. 2011).

The FTA strategy represents a relatively unique combination of top down and bottom up 'upscaling' and 'downscaling' (**Figure 1**). During the upscaling phase, terrestrial observations of rainfall are used to identify drought events, then large scale climate observations are evaluated, and then specific causal hypotheses are evaluated. Statistical evaluations and experiments with climate models can reinforce or weaken our confidence in specific causal factors. During the downscaling phase, evaluations of large scale climate tendencies are combined with interpolated station-based trend evaluations to produce projections of potential 2030 climate change. For example, since we believe that the recent observed drying trends across southern and southwestern Ethiopia are caused, at least in part, by large scale, long-term warming in the Indian and possibly western Pacific, it seems plausible to assume that drying trends may persist over the next few decades.

Our land cover analysis identified many transitions into cropland in the increasingly semiarid or arid south (**Figure 5**). Driven by population pressure, roads, and dense settlement patterns, this region is becoming more heavily cultivated. The intersection of rapid population growth, agricultural extensification, environmental degradation, and decreasing rainfall seems quite likely to result in increasing food and water security problems for this region.

This set of trends can be contrasted with conditions in the northwest of the country. Here, rainfall has been steady or increasing and the rate of cropland transitions and degradation is much lower than in the south. Extrapolated projections of 2010–39 average JJAS rainfall show that much of this region will very likely remain suitable for crop production. While developing the market, transport, and agricultural infrastructure to expand agriculture into these areas will prove a great challenge, national and international planning agencies should consider the relative climatic security of these regions as they formulate development plans. If Ethiopia could shift the center of its agricultural activity into regions of greater climatic security, its livelihoods would likely produce a much more reliable food supply and reduce its vulnerability. Investing in agricultural development, especially in areas that are currently climate secure areas, could also dramatically help improve production and lower price volatility. While the limited financial resources of poor agriculturalists make any progress difficult, Ethiopia's chronic and growing food insecurity could be addressed, at least in part, by vigorous and well planned development strategies. A thorough understanding of the local trends in land use, climate, and population should likely play a role in such planning.

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Volume 3

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Volume 3: Vulnerability of Energy to Climate

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CLIMATE VULNERABILITY

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VOLUME 3

VULNERABILITY OF ENERGY TO CLIMATE

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He has studied terrain-induced mesoscale systems, including the development of a three-dimensional mesoscale model of the sea breeze, for which he received the NOAA Distinguished Authorship Award for 1974. He has worked for NOAA's Experimental Meteorology Lab (1971—74), The University of Virginia (1974—81), and Colorado State University (1981—2006). He served as Colorado State Climatologist from 1999—2006. He was an adjunct faculty member in the Department of Civil and Environmental Engineering at Duke University in Durham, North Carolina (July 2003—06). He was a visiting professor in the Department of Atmospheric Sciences at the University of Arizona from October to December 2004.

He has served as chairman and member of the AMS Committee on Weather Forecasting and Analysis, and was the chief editor for the Monthly Weather Review for 5 years from 1981 to 1985. In 1977, he received the AMS Leroy Meisinger Award for ‘fundamental contributions to mesoscale meteorology through numerical modeling of the sea breeze and interaction among the mountains, oceans, boundary layer, and the free atmosphere’. He received the 1984 Abell New Faculty Research and Graduate Program Award, and also received the 1987/1988 Abell Research Faculty Award. He was declared ‘Researcher of the Year’ by the Colorado State University Research Foundation in 1993. In 2000, he received the Engineering Dean's Council Award from Colorado State University.

He authored a book published by Academic Press entitled ‘Mesoscale meteorological modeling’ in 1984 with a 2nd edition in 2002, a book for Routledge Press entitled ‘The Hurricane in 1990, a book (coauthored with W.R. Cotton) for Cambridge Press entitled ‘Human impacts on weather and climate in 1995; 2nd ed., 2006, a book (coauthored with R.A. Pielke, Jr.) entitled ‘Hurricanes: Their nature and impacts on society’ published in 1997 by John Wiley and Sons, and was co-chief editor (with R.A. Pielke, Jr.) of a book entitled ‘Storms’ published by Routledge Press in 1999.

He was elected as a fellow of the AMS in 1982 and fellow of the American Geophysical Union in 2004. From 1993—96, he served as editor-in-chief of the US National Science Report to the IUGG (1991—94) for the American Geophysical Union. From January 1996 to December 2000, he served as co-chief editor of the *Journal of Atmospheric Science*. In 1998, he received NOAA's ERL Outstanding Scientific Paper (with Conrad Ziegler and Tsengdar Lee) for a modeling study of the convective dryline. He was designated a Pennsylvania State Centennial Fellow in 1996, and named the Pennsylvania State College of Earth and Mineral Sciences Alumni of the year for 1999 (with Bill Cotton). He is currently serving on the AGU Focus Group on Natural Hazards (August 2009—Present) and the AMS Committee on Planned and Inadvertent Weather Modification (October 2009—Present). He is among one of three faculties and one of four members listed by ISI Highly Cited in Geosciences at Colorado State University and the University of Colorado at Boulder, respectively.

He has published over 370 papers in peer-reviewed journals, 55 chapters in books, coedited 9 books, and made over 700 presentations during his career to date. The listing of papers can be viewed at the project website: http://cires.colorado.edu/science/groups/pielke/pubs/. He also launched a science weblog in 2005 to discuss weather and climate issues. This weblog was named one of the 50 most popular Scienceblogs by Nature Magazine on 5 July 2006 and is located at http://pielkeclimatesci.wordpress.com/.

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VOLUME EDITORS

Dr Jimmy Adegoke is an award winning climate scientist whose research focuses on understanding the relationships between changing land surface processes and diverse indicators of environmental change. His recent work focuses on societal impacts of environmental change including air pollution studies in rapidly changing midlatitude urban areas and climate impacts on water resources in the Lake Chad Basin. He teaches at the University of Missouri-Kansas City (UMKC) where he served as chair of the Department of Geosciences from 2008—10. From August 2010 until very recently, he was Executive Director of the Council for Scientific and Industrial Research (CSIR) Natural Resources and Environment (NRE) Division, Pretoria, South Africa where he also served as the Director of the Applied Center for Climate and Earth Systems Science (ACCESS), a Center of Excellence (CoE) of the South Africa Department of Science and Technology (DST) Global Change Grand Challenge (GCGC) program. He is a member of several professional societies including the American Geophysical Union (AGU), Association of American Geographers (AAG), and American Meteorological Society (AMS). He is on the advisory council of the African Association for Remote Sensing of the Environment (AARSE) and also serves on the technical advisory committee of several United Nations applied science programs, including the United Nations Educational Scientific and Cultural Organization (UNESCO) crosscutting project on the application of remote sensing for water resources and ecosystem management in Africa. He lives in Kansas city where he served a 3-year team as an appointee of the Mayor of Kansas City Missouri (KCMO) on the city's Environmental Management Commission (EMC).

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Dr Dev Niyogi is an associate professor with joint appointment in the Departments of Agronomy and Earth, Atmospheric, and Planetary Science at Perdue University.

He is also the State Climatologist for Indiana and Director of the Indiana State Climate Office. His research seeks to advance the understanding of vegetation and land surface processes in environmental, weather forecasting, and climate analyses, using a combination of dynamical models and surface, satellite remote sensing, and multiscale analysis products.

His research deals with the understanding and representation of the effects of vegetation – land surface processes in environmental processes at different scales. He is one of the three invited, nonfederal representatives to the community modeling effort of the Weather Research and Forecast (WRF) model working group on Land Surface Models, and to the Federal Geophysical Data Commission (FGDC) Spatial Climate Working Group.

He has authored or coauthored 25 successful proposals for external grants totaling over $3M. He vertically integrates undergraduate, graduate, and postdoctoral researchers in his research and is very interdisciplinary in developing collaborative projects.

Dr George Kallos is a professor at the University of Athens, School of Physics, Division of Environmental Physics and Meteorology. He leads the Atmospheric Modeling and Weather Forecasting Group (AM & WFG). He has a BSc from the University of Athens/School of Mathematics (1975). He obtained his MSc (1983) and PhD (1985) in Geophysical Sciences/ Atmospheric Sciences Division, Georgia Institute of Technology, School of Geophysical Sciences, USA. He has 110 publications in peer review scientific journals, more than 230 presentations and publications in conference proceedings publications, 10 contributions in books and more than 200 other publications in subjects related to atmospheric physics and chemistry, sea-state conditions, and renewable energy production. He has been invited 70 times to give talks in conferences, seminars, etc. His published work has received >2000 citations. He has participated in 80 projects. He has organized 12 conferences related to air pollution and dust transport in the Mediterranean. He has supervised 10 PhDs and over 100 MSc theses and participated in 20 PhD examinations in Greece and Europe. He is an associate editor for the journals: '*Environmental Fluid Mechanics*', '*Advances in Meteorology*', '*International Journal of Geosciences*', '*Atmospheric Pollution Research*', and '*Journal of Aerospace Operations*'. He was awarded the International Union of Air Pollution Prevention Association – IUAPPA award for his work on 'Long-range transport and air quality work in the Mediterranean region'. His current research activities are related to atmospheric, climatic, air pollution, and sea-state model development and forecasting. He focuses in fully coupled modeling systems. The latest model developments are related to nucleation processes in clouds, desert dust cycle and its direct and indirect effects. Research activities related to renewable energy resources (wind, ocean, solar) are focusing on high accuracy atmospheric model development, energy relationships and predictions, and protection from extremes.

Timothy Seastedt received his BA in biology from the University of Montana, an MS degree in biological sciences from the University of Alaska at Fairbanks, and a PhD degree from the University of Georgia. He was on the faculty at Kansas State University and is currently a professor of Ecology and Evolutionary Biology and fellow of INSTAAR at the University of Colorado, Boulder. Much of his research has been conducted as part of the Long-Term Ecological Research (LTER) programs at KSU and CU. His interests focus on terrestrial ecosystem ecology and the causes and consequences of biotic change. His recent activities have emphasized the ongoing changes found along the grassland to (melting) glacier gradient that exists in the Colorado Front Range.

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Faisal Hossain received his PhD from the University of Connecticut in 2004. Prior to that, he had earned his MS and BS from the National University of Singapore and Indian Institute of Technology, Varanasi, respectively. He is currently an associate professor in the Department of Civil and Environmental Engineering where he received one of the highest awards of University – the Caplenor Research Award in 2012. His research interests comprise hydrologic remote sensing, uncertainty modeling of water cycle variables, human modification of extreme hydro-climatology, sustainable water resources engineering, space-borne transboundary water resources management, engineering education, and public outreach. He is also the recipient of awards such as NASA Earth System Science Fellowship (2002), Outstanding PhD Thesis Award (2005), NASA New Investigator Award (2008), American Society of Engineering Education (ASEE) Outstanding Research Award (2009), National Association of Environmental Professionals Education Excellence Award (2010), US Fulbright Faculty Award (2012), G.O.L.D. (Graduate Of the Last Decade) award from University of Connecticut (2012), and American Geophysical Union (AGU) Charles Falkenberg Award. He has published over 85 peer-reviewed journal articles, authored an undergraduate-level textbook, edited two book volumes, and contributed eight book chapters. His recent research on human modification of extreme events by artificial reservoirs has been featured by public media such as the BBC, National Geographic, New Scientist, Newsweek, Fox News, MSNBC, Wired.com, and German Public Radio. He served as an associate editor of *Journal of American Water Resources Association* from 2006–10. Currently, he serves as an associate editor for *Journal of Hydrometeorology* and a lead editor for the water volume of Elsevier Sciences five volume reference series on '*Climate Vulnerability: Understanding and Addressing Threats to Essential Resources*'.

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PREFACE

We are pleased to introduce the five-volume set of books on bottom-up, resource-based vulnerability assessments of the societally and environmentally key resources of water, food, energy, human health and well-being, and ecosystem function. This inclusive bottom-up vulnerability concept requires the determination of the major threats to these resources from climate, but also from other social and environmental issues. After these threats are identified for each resource, the relative risk from natural- and human-caused climate change (estimated from global climate model (GCM) projections, as well as the historical, paleorecord, and worst case sequences of events) can be compared with other environmental and social risks in order to adopt the optimal mitigation and adaptation strategies.

The bottom-up, resource-based approach (referred to by O'Brien (2009) as 'contextual vulnerability') that is the focus of the volume is distinct from the Intergovernmental Panel on Climate Change (IPCC) top-down assessment of vulnerability based on the multidecadal GCM predictions (projections) which O'Brien defined as 'outcome vulnerability' (**Table 1** and **Figure 1**).

An excellent example of the contextual vulnerability is the paper by Romero-Lankao et al. (2012) who concluded in a study of the literature that urban vulnerability is dominated by epidemiological studies and top-down assessments, but that inherent urban vulnerability and urban resilience approaches (the contextual vulnerability) are what is required in order to illuminate a more complete set of drivers of urban vulnerability. They also showed that the large majority of papers on vulnerability use the outcome vulnerability approach. However, as discussed below, this top-down approach has major flaws.

First, there is the issue that the term 'climate' has two definitions. The broader view (and the one adopted by NRC (2005)) is that climate consists of the atmosphere, oceans, land, and cryosphere. This is the preferred usage. The second definition is that climate is the term used for the long-term (e.g., multidecadal) statistics of weather.

As reported in the NRC (2005) report and written in the Pielke et al. (2009) article with respect to human climate forcings.

> In addition to greenhouse gas emissions, other first-order human climate forcings are important to understanding the future behavior of Earth's climate. These forcings are spatially heterogeneous and include the effect of aerosols on clouds and associated precipitation [e.g., Rosenfeld et al. 2008], the influence of aerosol deposition (e.g., black carbon (soot) [Flanner et al. 2007] and reactive nitrogen [Galloway et al. 2004]), and the role of changes in land use/land cover [e.g., Takata et al. 2009]. Among their effects is their role in altering atmospheric and ocean circulation features away from what they would be in the natural climate system [NRC 2005]. As with CO_2, the lengths of time that they affect the climate are estimated to be on multidecadal timescales and longer.

and

> "…the natural causes of climate variations and changes are important, as are the human influences. The human climate forcings involve a diverse range of first-order climate forcings, including, but not limited to, the human input of carbon dioxide (CO2). Most, if not all, of these human influences on regional and global climate will continue to be of concern during the coming decades."

Threats from climate involve any one or combination of climate variables as illustrated in **Figure 2**. There do not, of course, have to be changes in the statistics of these variables to constitute a risk. The term

Table 1 Contrast between a top-down versus bottom-up assessment of the vulnerability of resources to climate variability and change

Approach	*Comparative vulnerability*	*Contextual vulnerability*
Assumed dominant stress	Climate, recent greenhouse gas emissions to the atmosphere, ocean temperatures, aerosols, etc.	Multiple stresses: climate (historical climate variability, land use and water use, altered disturbance regimes, invasive species, contaminants/pollutants, habitat loss, etc.)
Usual timeframe of concern	Long-term, doubled CO_2 30–100 years in the future.	Short-term (0–30 years) and long-term research.
Usual scale of concern	Global, sometimes regional. Local scale needs downscaling techniques. However, there is little evidence to suggest that present models provide realistic, accurate, or precise climate scenarios at local or regional scales.	Local, regional, national, and global scales.
Major parameters of concern	Spatially averaged changes in mean temperatures and precipitation in fairly large grid cells with some regional scenarios for drought.	Potential extreme values in multiple parameters (temperature, precipitations, frost-free days) and additional focus on extreme events (floods, fires, droughts, etc.) measures of uncertainty.
Major limitations for developing coping strategies	Focus on single stress limits preparedness for other stresses. Results often show gradual ramping of climate change-limiting preparedness for extreme events. Results represent only a limited subset of all likely future outcomes – usually unidirectional trends. Results are accepted by many scientists, the media, and the public as actual 'predictions'. Lost in the translation of results is that all models of the distant future have unstated (presently unknowable) levels of certainty or probability.	Approach requires detailed data on multiple stresses and their interactions at local, regional, national, and global scales, and many areas lack adequate information. Emphasis on short-term issues may limit preparedness for abrupt "threshold" changes in climate sometime in the short or long term. Requires preparedness for a far greater variation of possible futures, including abrupt changes in any direction – this is probably more realistic, yet difficult.

Adapted from Kabat et al. 2004.

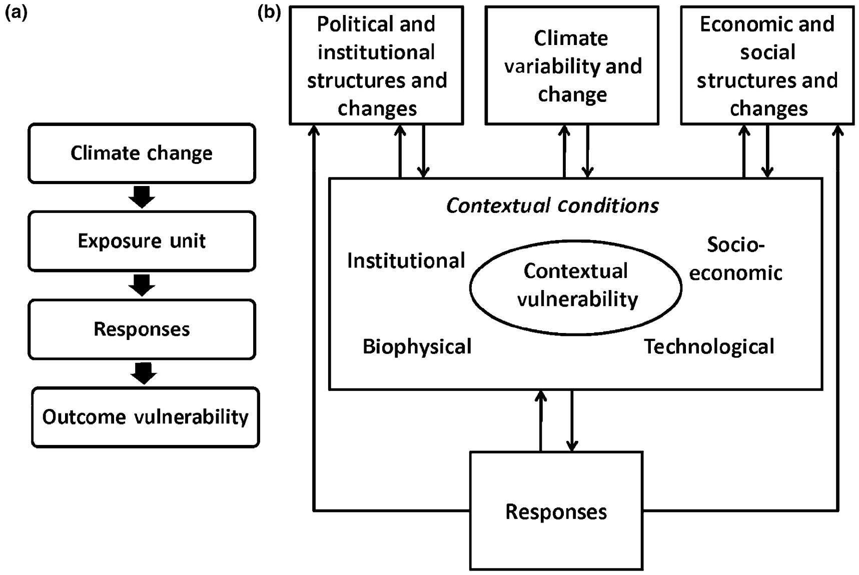
(a)
Climate change
Exposure unit
Responses
Outcome vulnerability
(b)
Political and institutional structures and changes
Climate variability and change
Economic and social structures and changes
Contextual conditions
Institutional
Socio-economic
Contextual vulnerability
Biophysical
Technological
Responses

Figure 1 Framework depicting two interpretations of vulnerability to climate change: (a) outcome vulnerability and (b) contextual vulnerability. *From: Füssel (2009) and O'Brien et al. (2007).*

'climate change' should be used to describe any multidecadal or longer alteration in one or more physical, chemical, and/or biological components of the climate system, but as explained below, this terminology has morphed into multiple, diverse (and often mutually exclusive) definitions as used by the impacts communities.

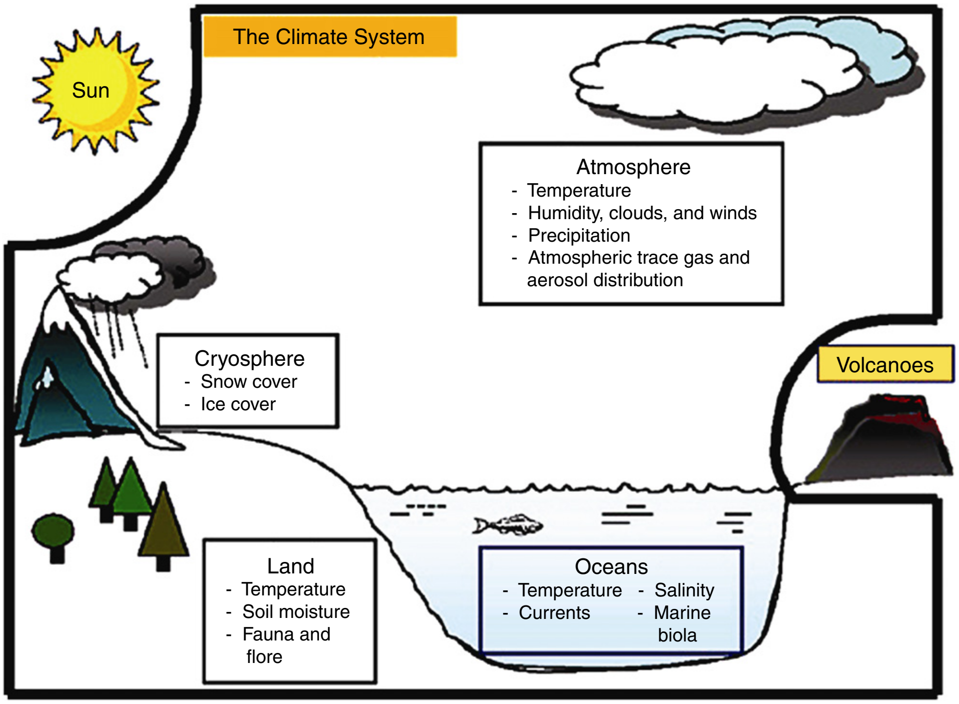
The Climate System
Sun
Atmosphere
- Temperature
- Humidity, clouds, and winds
- Precipitation
- Atmospheric trace gas and aerosol distribution
Cryosphere
- Snow cover
- Ice cover
Volcanoes
Land
- Temperature
- Soil moisture
- Fauna and flore
Oceans
- Temperature
- Currents
- Salinity
- Marine biola

Figure 2 The climate system, consisting of the atmosphere, oceans, land, and cryosphere. Important state variables for each sphere of the climate system are listed in the boxes. For the purposes of this report, the Sun, volcanic emissions, and human-caused emissions of greenhouse gases and changes to the land surface are considered external to the climate system (NRC 2005).

First, climate is never static (Lovejoy and Schertzer 2012). As written in Rial et al. (2004)

> "The Earth's climate system is highly nonlinear: inputs and outputs are not proportional, change is often episodic and abrupt, rather than slow and gradual, and multiple equilibria are the norm."

The assumption of a stable climate system (e.g., the reason for the use of the terminology 'climate stabilization') in the absence of human intervention is a mischaracterization of the behavior of the real climate system. Humans are now adding to the complexity of forcings and feedbacks, but change has always been a part of the climate system. 'Climate change' is, and always has, been occurring. The added word 'change' is, therefore, redundant.

Moreover, there are additional misunderstandings. 'Global warming', which is an increase in the global annual average heat content measured in Joules, is often incorrectly equated to mean 'climate change'. Global warming, however, is just a subset of "climate change."

The term 'climate change', is also being erroneously used to mean only 'anthropogenic caused changes in climate' from nearly 'static' climatic conditions. Frequently, just the human input of greenhouse gases is assumed to be the reason for 'climate change'. For example, NRC (2010) (Climate Stabilization Targets: Emissions, Concentrations, and Impacts Over Decades to Millennia (2010)) states

> "This new report from the National Research Council concludes that emissions of carbon dioxide from the burning of fossil fuels have ushered in a new epoch where human activities will largely determine the evolution of Earth's climate."

Thus, the recommendations to the authors of the volume (not always accepted) were to replace terminology, such as climate change, climate stabilization, and climate disruption, with accurate terminology. When changes in climatic conditions are discussed, it was requested that the actual climate variables (such as temperature, precipitation, length of growing season) that are being altered, be specified. Phrases such as 'changes in regional and global climate statistics' could also be used.

There is a very fundamental reason to limit the use of 'climate change' by the impacts community. Key societal and environmental resources, such as water, food, energy, ecosystem function, and human health respond to climate, not just to an incremental change in the climatic conditions. As noted earlier, the assumption of a stable climate system, in the absence of human intervention, is a mischaracterization of the behavior of the real climate system.

However, some authors retained the use of the terminology 'climate change'. It was acquiesced as long as there was a significant contribution in their chapter to a broad-based assessment of risk to the key resource they were discussing.

Another misused term is 'global change', when really what is almost always meant is a local and/or regional change in the environmental conditions, including from climate. The accurate terminology should be 'environmental change'. The term 'environmental change' is, therefore, preferred rather than 'global change', as the latter terminology is very much a top-down viewpoint. Almost all impacts on key resources are on the local and regional scale.

We also requested the authors start with the risks and factor in the climate threats after thresholds, etc. were first obtained. This was not done in some chapters, but this information can still be extracted from the text. Obtaining the spectrum of risks first is the more inclusive way to assess threats to key resources, and thus, in the view, to prepare the optimal mitigation and adaptation strategies.

For the climate component of risk, the outcome vulnerability (the top-down) approach relies on skillful weather predictions and analyzes with a regional and a local focus. For weather prediction on time periods of days to a week or two, excellent skillful predictions are available for use in outcome vulnerability assessments. On seasonal timescales, there is also some limited predictive skill to apply to outcome vulnerability assessments, particularly for such well-defined weather events such as an El Niño or La Niña (Castro et al. 2007). However, for decadal and multidecadal predictions little, if any, predictive skill has been shown in hindcast climate model predictions of changes in regional weather statistics beyond what is available to the impacts community via the historical, recent paleorecord and a worst case sequence of weather events.

To illustrate the lack of skill, the conclusions from several papers have been summarized. Fyfe et al. (2011) concluded that

> "….for longer term decadal hindcasts a linear trend correction may be required if the model does not reproduce long-term trends. For this reason, we correct for systematic long-term trend biases."

Xu and Yang (2012) find that without tuning from real world observations, the model predictions are in significant error. For example, they found that

> …the traditional dynamic downscaling (TDD) [i.e. without tuning) overestimates precipitation by 0.5-1.5 mm d-1…..The 2-year return level of summer daily maximum temperature simulated by the TDD is underestimated by 2-6°C over the central United States-Canada region."

The paper van Oldenborgh et al. (2012) report just limited predictive skill in two regions of the oceans on the decadal time period, but no regional skill elsewhere, when they conclude that:

> "A 4-model 12-member ensemble of 10-yr hindcasts has been analysed for skill in SST, 2m temperature and precipitation. The main source of skill in temperature is the trend, which is primarily forced by greenhouse gases and aerosols. This trend contributes almost everywhere to the skill. Variation in the global mean temperature around the trend does not have any skill beyond the first year. However, regionally there appears to be skill beyond the trend in the two areas of well-known low-frequency variability: SST in parts of the North Atlantic and Pacific Oceans is predicted better than persistence. A comparison with the CMIP3 ensemble shows that the skill in the northern North Atlantic and eastern Pacific is most likely due to the initialisation, whereas the skill in the subtropical North Atlantic and western North Pacific are probably due to the forcing."

Anagnostopoulos et al. (2010) report that

> "…. local projections do not correlate well with observed measurements. Furthermore, we found that the correlation at a large spatial scale, i.e. the contiguous USA, is worse than [even] at the local scale."

Stephens et al. (2010) wrote

> "models produce precipitation approximately twice as often as that observed and make rainfall far too lightly…..The differences in the character of model precipitation are systemic and have a number of important implications for modeling the coupled Earth system …….little skill in precipitation [is] calculated at individual grid points, and thus applications involving downscaling of grid point precipitation to yet even finer-scale resolution has little foundation and relevance to the real Earth system."

van Haren et al. (2012) concluded from their study with respect to climate model predictions of precipitation that

> "An investigation of precipitation trends in two multi-model ensembles including both global and regional climate models shows that these models fail to reproduce the observed trends….. A quantitative understanding of the causes of these trends is needed so that climate model based projections of future climate can be corrected for these precipitation trend biases…. To conclude, modeled atmospheric circulation and SST trends over the past century are significantly different from the observed ones."

Sun et al. (2012) found that

> "…in global climate models, [t]he radiation sampling error due to infrequent radiation calculations is investigated …….. It is found that…. errors are very large, exceeding 800 W m^{-2} at many non-radiation time steps due to ignoring the effects of clouds…."

There is an important summary of the limitations in multidecadal regional climate predictions in Kundzewicz and Stakhiv (2010) who succinctly conclude that

> "Simply put, the current suite of climate models were not developed to provide the level of accuracy required for adaptation-type analysis."

Since the top-down outcome vulnerability approach depends on skillful decadal and longer regional and local climate predictions, yet they have shown little if any skill, another approach is needed.

For this reason, the volume set of five books presents an alternate approach — the bottom-up, resource-based outcome (contextual) vulnerability perspective. The goal of the set was to focus on the climate component of stress but also consider, in-depth, other environmental and social threats.

The text of the articles is written at a level that allows undergraduate students to understand the material, while providing active researchers with a ready reference resource for information in the respective field.

The questions requested to the authors address with respect to a specific resource were:

1. Why is this resource important? How is it used? To what stakeholders is it valuable?
2. What are the key environmental and social variables that influence this resource?
3. What is the sensitivity of this resource to changes in each of these key variables? This includes, but is not limited to, the sensitivity of the resource to climate variations and change on short (e.g., days), medium (e.g., seasons), and long (e.g., multidecadal) timescales.
4. What changes (thresholds) in these key variables would have to occur to result in a negative (or positive) response to this resource?
5. What are the best estimates of the probabilities for these changes to occur? What tools are available to quantify the effect of these changes? Can these estimates be skillfully predicted?
6. What actions (adaptation/mitigation) can be undertaken in order to minimize or eliminate the negative consequences of these changes (or to optimize a positive response)?
7. What are specific recommendations for policymakers and other stakeholders?

There are also overview chapters that discuss the science of the resource.

Several authors insisted on focusing on the use of the outcome vulnerability (top-down) approach based on the multidecadal GCM projections (statistically or dynamically downscaled) as the starting point of their chapters. The chapters were accepted, despite this shortcoming, because when they finally discussed adaptation in their text, they did present the broader-based bottom-up focus that is the centerpiece of the volume. Readers,

however, need to be aware that the top-down, GCM scenarios are only a subset, at best, of what is plausible in the coming decades. Multidecadal predictions of changes in regional and local climate statistics have not shown skill when run in a hindcast mode for the past several decades.

In summary, the goal of the five-volume set of books is to document the value of a bottom-up, resource-based assessment of risk to key resources, as illustrated schematically in Figure 3a–e. Most, but not all, authors accepted this framework. This can be assessed without having any predictability on

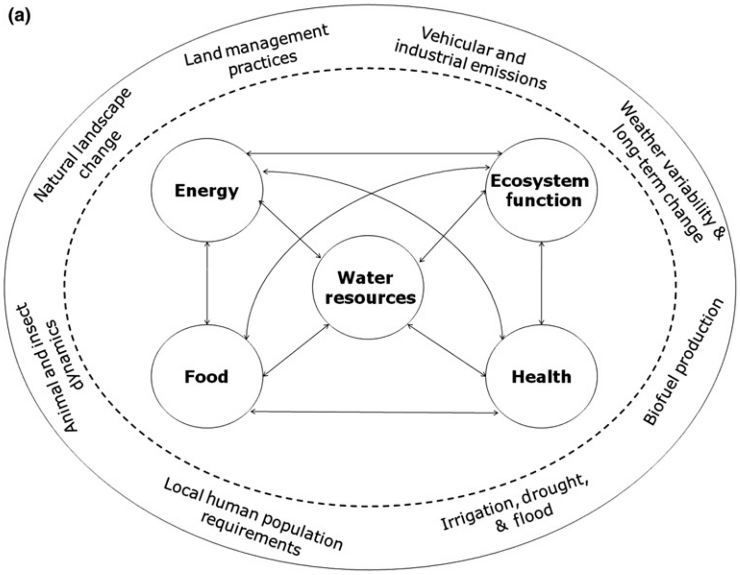
(a)
Land management practices
Vehicular and industrial emissions
Natural landscape change
Weather variability & long-term change
Energy
Ecosystem function
Water resources
Food
Health
Animal and insect dynamics
Biofuel production
Local human population requirements
Irrigation, drought, & flood

Figure 3a Contextual vulnerability for water resources (Hossain: Editor)

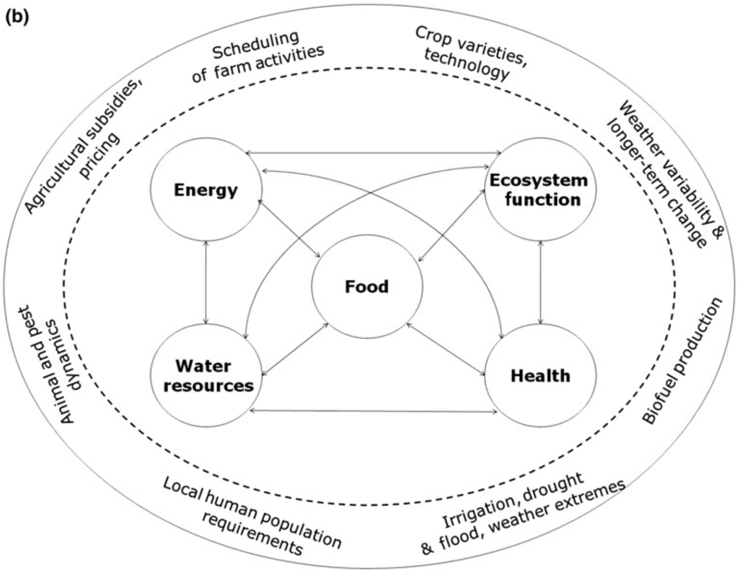
(b)
Scheduling of farm activities
Crop varieties, technology
Agricultural subsidies, pricing
Weather variability & longer-term change
Energy
Ecosystem function
Food
Water resources
Health
Animal and pest dynamics
Biofuel production
Local human population requirements
Irrigation, drought & flood, weather extremes

Figure 3b Contextual vulnerability for food (Niyogi: Editor).

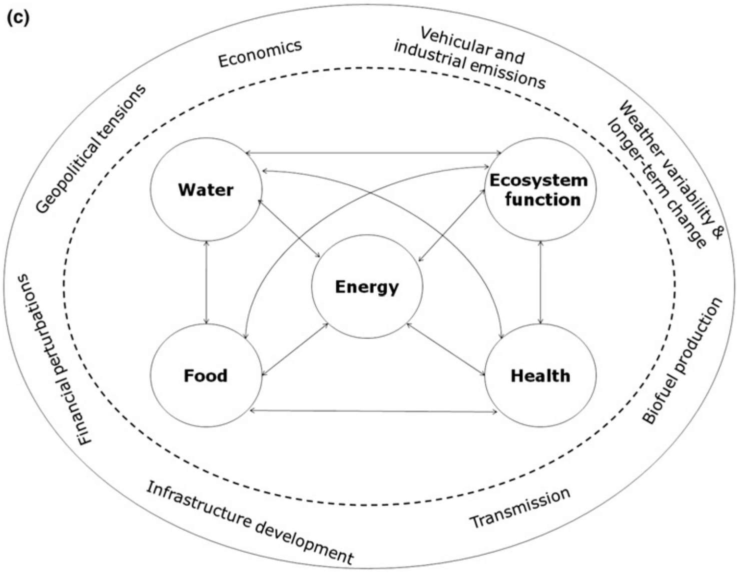
(c)
Economics
Vehicular and industrial emissions
Geopolitical tensions
Weather variability & longer-term change
Water
Ecosystem function
Energy
Food
Health
Financial perturbations
Biofuel production
Infrastructure development
Transmission

Figure 3c Contextual vulnerability for energy (Kallos: Editor).

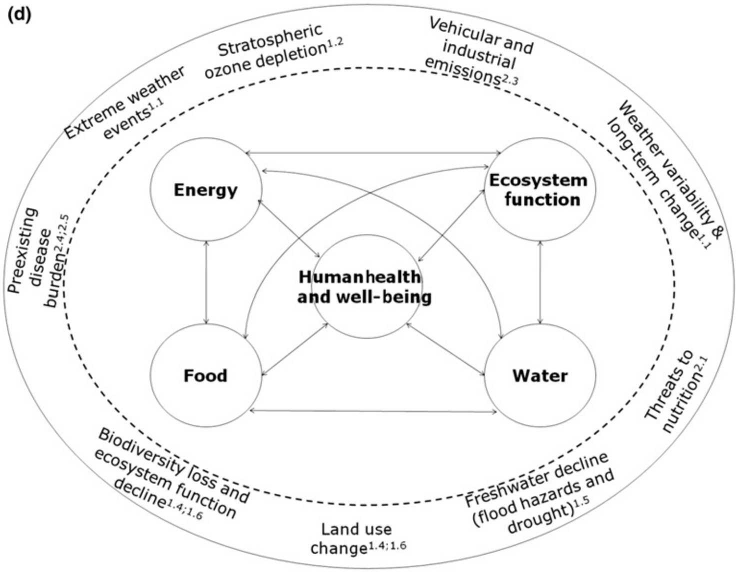
(d)
Stratospheric ozone depletion$^{1.2}$
Vehicular and industrial emissions$^{2.3}$
Extreme weather events$^{1.1}$
Weather variability & long-term change$^{1.1}$
Energy
Ecosystem function
Preexisting disease burden$^{2.4;2.5}$
Humanhealth and well-being
Food
Water
Threats to nutrition$^{2.1}$
Biodiversity loss and ecosystem function decline$^{1.4;1.6}$
Land use change$^{1.4;1.6}$
Freshwater decline (flood hazards and drought)$^{1.5}$

Figure 3d Contextual vulnerability for human health and well-being (Adegoke and Wright Editors).

multidecadal time periods. It is an alternative (and more inclusive) perspective than the IPCC top-down outcome vulnerability approach which starts with the GCMs as the overarching framework. In the bottom-up approach, the scenarios from the GCM predictions should only enter after the specific threats to the resources are determined and even then, they provide, at best, a limited set of insights into what is possible.

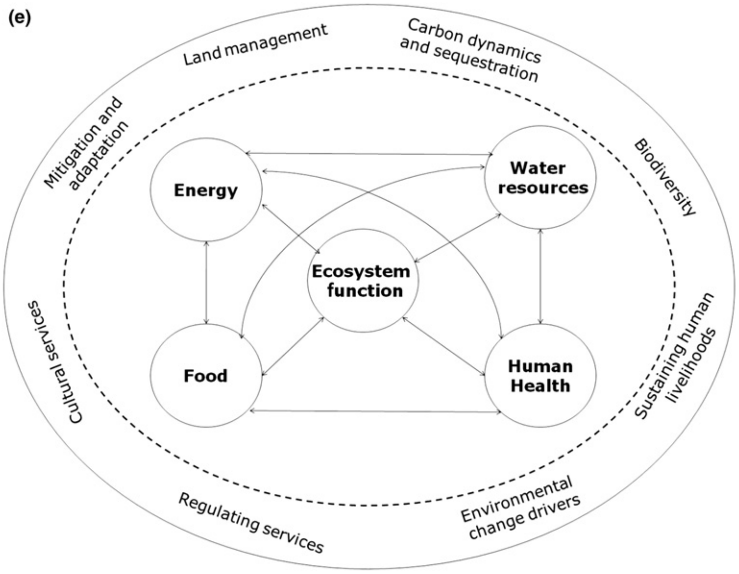
(e)
Land management
Carbon dynamics and sequestration
Mitigation and adaptation
Biodiversity
Energy
Water resources
Ecosystem function
Food
Human Health
Cultural services
Sustaining human livelihoods
Regulating services
Environmental change drivers

Figure 3e Contextual vulnerability for ecosystem function (Seastedt and Suding; Editors).

We look forward to feedback from the readers.

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Jimmy Adegoke,
Faisal Hossain,
George Kallos,
Dev Niyogi,
Timothy Seastedt,
Katharine Suding,
Caradee Y. Wright and
Dallas Staley

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Preface - Vulnerability of Energy to Climate

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Water and therefore water resources can be considered of great importance for this planet; however, energy and energy resources are also recognized as paramount for maintaining life. Since the appearance of life on Earth, energy resources have been of crucial significance. Fire was the primary energy resource that changed the life of the first people on Earth. Energy resources were different through the centuries, but their resources were always vulnerable to different factors, and control of these resources was always a major issue. Energy resources may vary over time, but always remain vulnerable because of human activities and/or natural causes. For example, wood was a major source for maintaining fire for various human activities. Extended fires resulting from human intervention or natural activities (e.g., lightning) cleared large areas and forced the population to migrate, causing tensions with other tribes. Elemental energy resources (mainly wood) were more vulnerable in arid and semiarid regions of the planet because of the slow growth of vegetation and limited water availability. The use of fossil fuel as an energy resource during the preindustrial period was limited mainly to metal processing.

During the industrial era, energy resources became more and more important for sustainability and growth. The new energy resources also became more vulnerable to natural and mainly to human intervention. The most well-known new energy resources used during the industrial period were fossil fuels, mainly coal and oil. Exploitation of these energy resources had several consequences to the environment and society. Extraction and use of this energy required more and more complicated technology; therefore, vulnerability to disruption increased.

Several things changed concerning energy resources and their vulnerability after the invention of electricity and its use in homes and industry. Electrical networks, as well as oil and gas pipeline networks, became complicated, and transmission lines became more vulnerable to extreme weather events and other natural hazards (e.g., blackouts in California).

A major energy resource was added during the second half of the twentieth century – nuclear energy. Nuclear energy is vulnerable to a series of natural hazards such as extreme weather events, seismic activity, and tsunamis. (Note the recent event in Fukushima, Japan.)

Currently, renewable energy resources occupy more and more of the energy portfolio, with wind being the major source, followed by solar and biomass. Ocean energy occurs in different forms, but wave, tidal, sea current, and biomass growth are the most important ones. Ocean energy is currently only in an experimental phase, but is a promising energy resource for the future. Large ocean platforms for energy production are facing serious problems associated with extreme weather events and technological limitations. Renewable energy resources are vulnerable mainly to extreme weather and less to climate fluctuations.

Energy resources and distribution networks are controlled and managed by established markets. Today's markets have become complicated, and to a certain degree control the economic activities of the entire planet. Market vulnerability results from several factors, such as geopolitical tensions, financial perturbations, extreme weather events, and of course long-term climatic variability.

This volume covers important issues of various energy resources and discusses vulnerability issues. As in the other volumes of this climate encyclopedia, the bottom-up approach has been adopted. This approach is considered the most appropriate for decision making or adaptation compared with the top-down, outcome-oriented approach widely used in vulnerability studies.

This book volume aims to ask some basic questions which include the following:

- What are the key issues related to different kinds of energy resources?
- What are the major threats to these resources, and how vulnerable are they?
- What are the most important factors that affect energy vulnerability?
- How vulnerable are energy resources and their distribution networks to weather and climate?
- What do we have to do to maintain sustainability through the rational use of energy resources, with a special focus on those that are limited?

The volume is divided into four major sections. The first deals with energy, environment, and climate issues; the second with the vulnerability of various energy resources such as fossil fuels, nuclear energy, renewable, and hydropower; the third deals with energy production, conversion, transmission, distribution, policy, planning, and mitigation processes; and the fourth discusses networks and markets. The reader will find general information, although highly technical information is included in some chapters.

Thanks to all the contributing authors for the dedicated work they have collected and discussed in this volume. I hope the readers will find it a unique source of information.

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3.01 Climate and Energy Vulnerability in Coastal Regions: The Case for US Pacific and Northeast Corridor Coastal Regions

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Glossary

Air basin An area with a geographical structure or climatic condition that results in relatively little movement of air in or out of the area.

General circulation models (GCM) A mathematical model of the general circulation of a planetary atmosphere or ocean. It is based on the Navier–Stokes equations on a rotating sphere with thermodynamic terms for various energy sources (radiation, latent heat).

Greenhouse gas (GHG) A gas in an atmosphere that absorbs and emits radiation within the thermal infrared range.

Northeast corridor (NEC) A region consisting of Pennsylvania, New Jersey, New York, Vermont, Connecticut, Massachusetts, Delaware, New Hampshire, Maine, and the District of Columbia.

Southern California Air Basin (SoCAB) One of several geopolitical areas designed by the state of California for the purpose of air quality management. Includes all of Orange County and Los Angeles County and the nondesert regions of Riverside County and San Bernardino County.

The Special Report on Emissions Scenarios (SRES) A report by the Intergovernmental Panel on Climate Change (IPCC) that was published in 2000. The greenhouse gas emissions scenarios described in the report have been used to make projections of possible future climate change.

Statistical significance: In statistics, a result is called "statistically significant" at a given probability if it is unlikely to have occurred by chance at that level of probability.

Upwelling An oceanographic phenomenon that involves wind-driven motion of dense, cooler, and usually nutrient-rich water toward the ocean surface, replacing the warmer, usually nutrient-depleted surface water.

Urban heat island (UHI) An excess warmth of a metropolitan area over its surrounding rural areas. The main cause of the urban heat island is modification of the land surface by urban development which uses materials that effectively retain heat.

3.01.1 Introduction

Energy infrastructure and activity may be one of the most sensitive aspects of society to a climate in terms of demands, availability, and vulnerability. Climate defines, to a large degree, human comfort levels for space heating and cooling, and these demands are manifested differently in geographical locations. A warming climate may represent increased energy demands in tropical regions or decreased energy demands under winter conditions in high latitude regions. Climate trends may also represent high risk factors to the energy infrastructure when exposed to frequent and extended extreme

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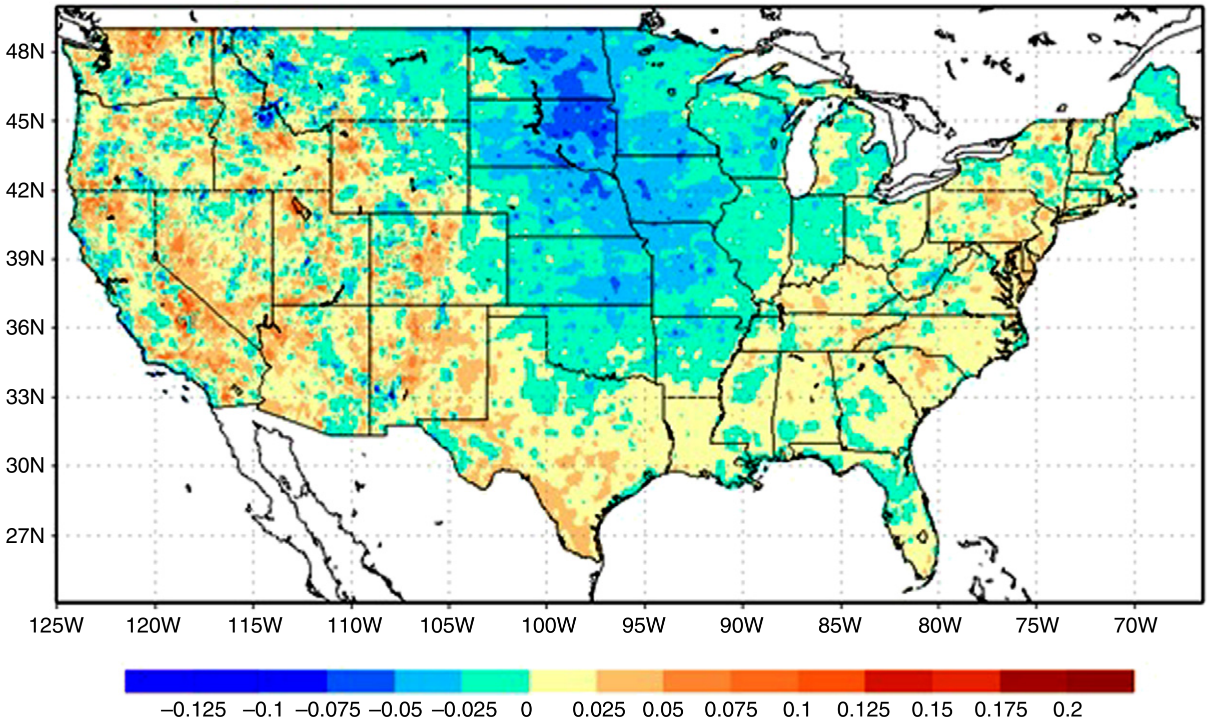


Figure 1 JJA Prism (4 km resolution) maximum-temperature trends for the period of 1970–2010 (°C decade^{-1}).

conditions such as heat waves or winter storms. This chapter focuses on reviewing and analyzing the connections between climate trends and energy for the case of the coastal regions of the United States. Coastal regions represent an interesting case characterized by high population, sensitivity to climate trends, and as will be seen in this chapter, results that seem to contradict ones anticipated common sense.

We will start with the fact that the climate is changing, as reflected in previous chapters of this book. This fact is again emphasized in Figures 1 and 2 (The PRISM Climate Group 2012), which show the trends of extreme surface temperatures, maximum and minimum, for the continental United States. We may expect that given the almost uniform warming trend of minimum temperatures, energy demands for heating may be reducing, with contrasting expectations for summer conditions. These general patterns and expectations may be correct in the overall context of total energy trends, as shown in Figure 3 (EIA 2011; U.S. Census 2009), which clearly shows an increasing trend in overall US electrical energy consumption and a reduction in natural gas consumption. The fundamental question of how precisely climate influences these trends is still unanswered. Figure 1 shows some exceptions from maximum-temperature trends, such as coastal California, where maximum temperatures have a decreasing trend. The specific question of connections between climate and energy in these regional scales should also be of major interest to the reader. The spatial distribution of total energy (both electricity and gas; Figures 4 and 5) suggests, in general, a correlation between reduced energy for space heating and increasing maximum temperatures; however, this is not clearly evident with trends on total electricity. Figure 4 shows overall increases in electricity for all states, with reduced increases in the Western Pacific and in other Northeastern coastal regions.

This chapter looks in-depth at the question of nexus between energy and climate trends by presenting an analysis and methodology for the US coastal areas of California and the Northeast Corridor region, including surface temperature trends, extreme events, spatial and temporal energy trends on a per sector basis, and possible reflections on CO_2 production. The presented methodology can be applied to almost any location around the globe.

3.01.2 Energy Trends in California

Energy activity is linked to climate trends in several ways. From the demand side, energy for space heating and cooling in buildings directly correlates to variability of surface temperature and humidity conditions. Buildings in general consume more than 30% of overall energy in the United States (Kreider et al. 2010). The relationship between energy and climate variability is investigated in detail for California and reported in this section. The analysis first considers degree-day analysis, followed by energy trends in demand sectors impacted by climate, including extremes.

3.01.2.1 Relationship between Energy and Climate in Coastal California

Degree-day analysis is the simplest method used for energy studies and is appropriate if energy used in buildings represents a significant component of the total energy budget (ASHRAE,

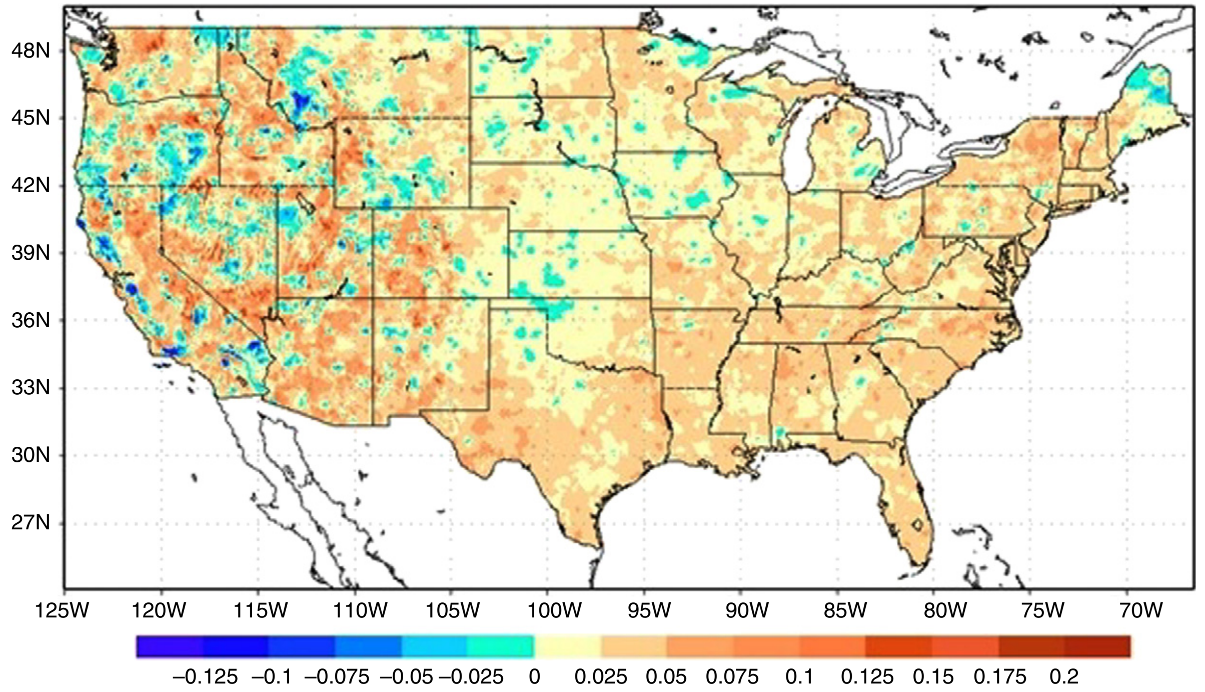

48N
45N
42N
39N
36N
33N
30N
27N
125W
120W
115W
110W
105W
100W
95W
90W
85W
80W
75W
70W
−0.125
−0.1
−0.075
−0.05
−0.025
0
0.025
0.05
0.075
0.1
0.125
0.15
0.175
0.2

Figure 2 Same as **Figure 1**, but for minimum temperature.

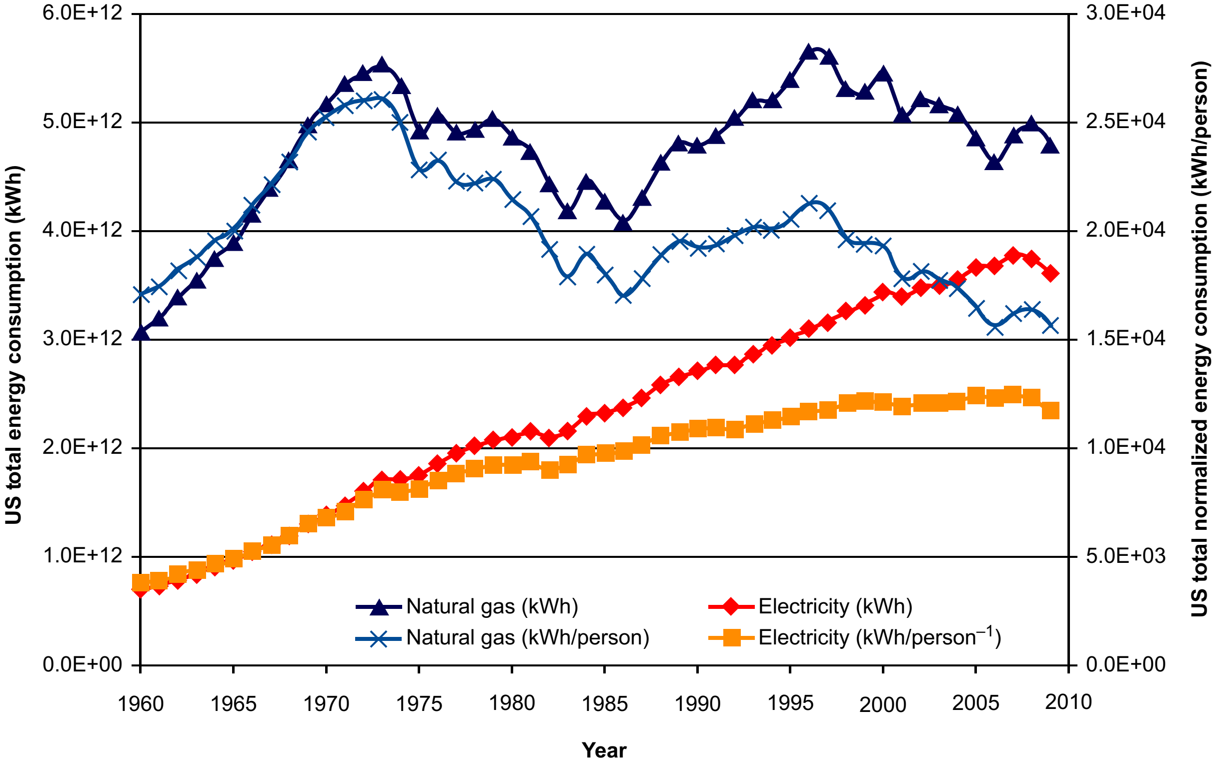


Figure 3 US total energy consumption 1960–2009.

2005). Although computers can easily calculate the energy consumption of buildings, the concept of degree-days remains a valuable tool since a climate's severity can be concisely characterized in terms of degree-days. Also, the degree-day method and its generalizations can provide a simple estimate of annual loads. Such estimates can be accurate if the indoor temperature and internal gains are relatively constant and if the heating or cooling systems operate for a complete season (ASHRAE, 2005).

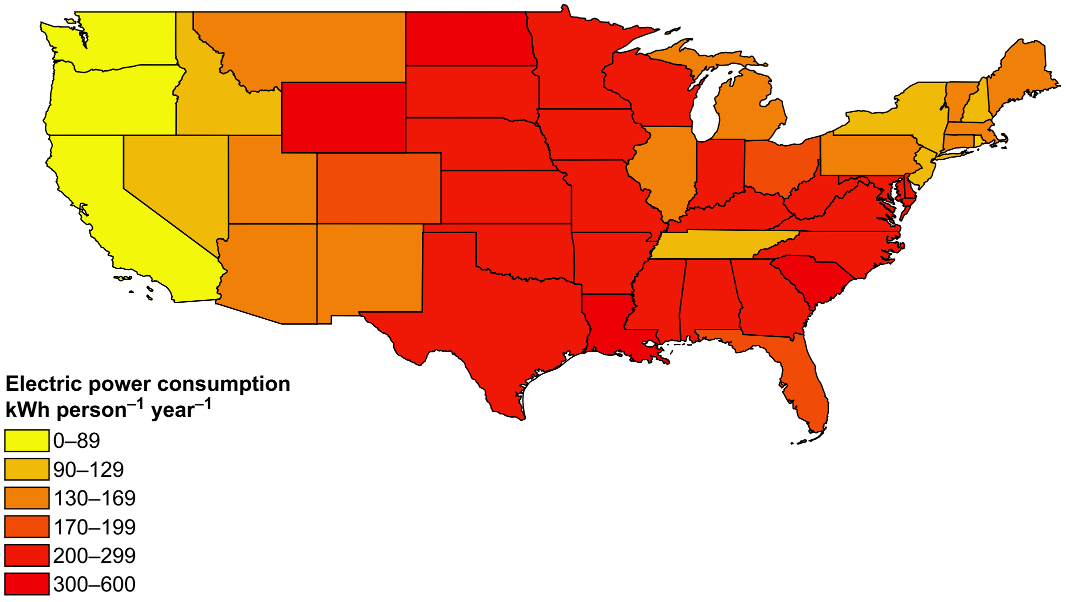

Electric power consumption
kWh person^{-1} year^{-1}
0–89
90–129
130–169
170–199
200–299
300–600

Figure 4 US electric power consumption per capita 1960–2009 by state.

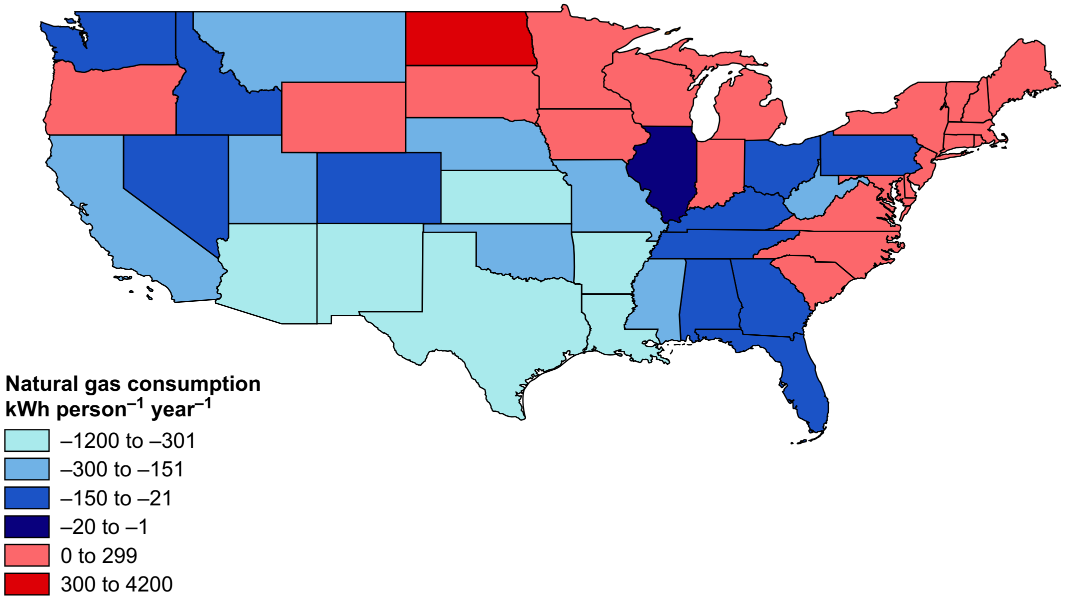

Natural gas consumption
kWh person^{-1} year^{-1}
–1200 to –301
–300 to –151
–150 to –21
–20 to –1
0 to 299
300 to 4200

Figure 5 US natural gas consumption per capita 1960–2009 by state.

In a general sense, degree-day analyses estimate the increase or decrease in temperature needed for a building using a base temperature (T_{base}) and defined as the temperature at which a building reaches thermal equilibrium with the incoming energy and the environment. In this study, the T_{base} is assumed to be 18 °C, which represents average steady-state conditions in typical buildings. Summer hot days require the use of energy for cooling, as measured in Cooling Degree Day (CDD) values, while winter heating requirements are measured in Heating Degree Day (HDD) values.

To compute CDD or HDD values, the average temperature for a day (T_{day}) is estimated and T_{base} is subtracted; if the difference is positive, the day is a CDD, and if negative it is an HDD, as follows:

$$\text{CDD or HDD} = \sum_{1}^{n} (T_{\text{day}} - T_{\text{base}})$$

where n is the number of days in the month. The sum of all daily CDD and HDD values is the total monthly CDD and HDD value. In this study, T_{day} is assumed to be the average between the values of daily $T_{\max}$ and $T_{\min}$.

Many studies have used CDDs and HDDs from average-temperature data. Thom analyzed climatological degree-day (DD) trends with an empirical truncation coefficient related to

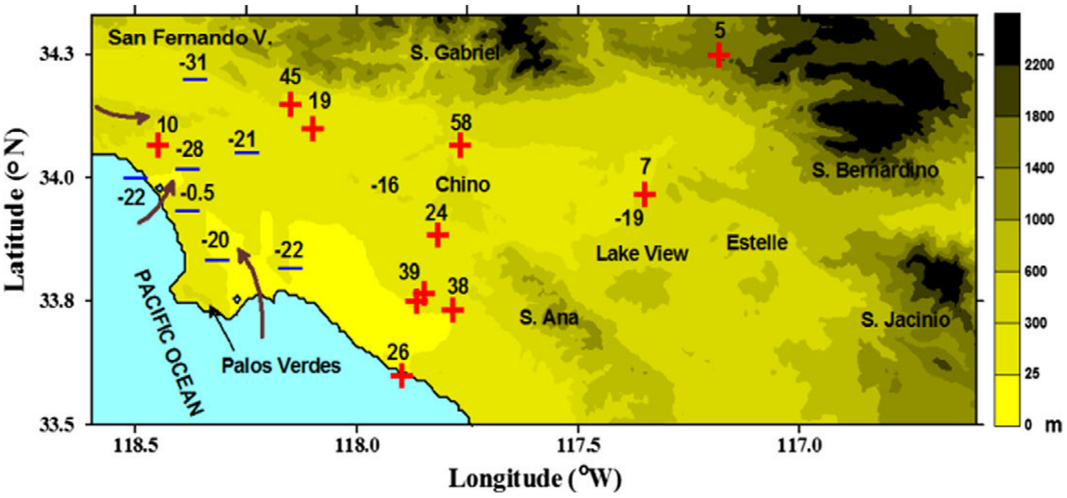


Figure 6 Spatial distributions of 1970–2005 summer CDD trends (DD decade^{-1}, where red pluses show increasing values and blue dashes show decreasing values) for the SoCAB (Lebassi et al. 2010).

monthly DD values. Thom analyzed the relationship between mean monthly DDs below a T_{base} of 18 °C and mean monthly temperatures by deriving probability functions of DD from probability functions of temperatures (Thom 1952). He later extended this by use of an unmodified truncation coefficient for any base temperature by modifying the truncation coefficient (Thom 1954, 1966). Downton et al. (1988) analyzed the National Climatic Data Center (NCDC) annual DD data from 1895 to 1983 and they found that historical population shifts affect US energy demands for cooling and heating. Quayle and Diaz (1980) used electric and fuel consumption data for individual residences, performed a regression analysis relating energy consumption and HDD totals, and concluded that short-term energy projections can be generated from accurate weather predictions. Diaz and Holle (1984) further analyzed the census data from 48 US states and studied the impact of population shifts from cooler-wetter regions to hotter-drier regions, which resulted in relatively lower heating needs but larger cooling needs nationwide. Most recently, Kolokotroni et al. (2010) using HDDs and Cooling Degree Hours (CDHs) developed a method for predicting air temperatures within the Urban Heat Island (UHI), which is a very reliable tool for use as part of the process of predicting heating and cooling loads for urban buildings.

Other studies have focused on impacts from climate change on the energy sector in California. Other works (Miller et al. 2008; Franco and Sanstad 2008; Franco 2005; Edwards, 1991; Darmstadter 1993; CEC 2006; Baxter and Calandri 1992) have reported energy-demand increases due to Greenhouse gas (GHG) warming, in general, and increases in summertime electricity consumption to create comfortable temperatures in indoor spaces.

A similar analysis was performed for the CDD and HDD values at the two California air basins previously discussed (Lebassi et al. 2010). Using daily data from Cooperative (COOP) stations, this analysis considered spatial trend distributions for 1970–2005 June–July–August CDD and December–January–February HDD values at the two air basins. The following analysis expands the study of the two California air basins to the whole state of California.

Results in the Southern California Air Basin (SoCAB) (Figure 6) show that most low-elevation coastal sites in the area have decreasing June–July–August CDD values consistent with falling average temperatures, while most inland and high-elevation stations show even larger increases consistent with GHG warming. Since the topography is much more complex in the San Francisco Bay Area (SFBA) and Central valley regions, so is its June–July–August CDD pattern. Only the areas that are open to marine air penetration through sea-level gaps and splits show decreasing CDD values; on the other hand, most high-elevation coastal sites, as well as inland sites and areas where the coastal mountains have blocked the sea breeze, show increasing values (Figure 7). The winter HDD trends are far more obvious than the summer CDD trends since marine influences are weaker during the winter and GHG warming features are dominant during that season. This is reflected in consistent decreasing HDD values in the majority of the locations in both air basins (Figures 8 and 9), which translates into warming winters.

Extended analyses for the rest of the state indicate that the same patterns are observed in the entire state and not only in the two air basins. Figure 10 shows that most of the cooling summer CDD trends are located in a narrow strip along the coast with a width of approximately 70 km as well as most low-elevation coastal sites. On the other hand, Figure 11 indicates the decreasing winter HDD trends all over the state except for a few isolated points, reflecting a warmer winter in the entire region during the past four decades. The implications of these trends in DD in actual energy demands are discussed in the following subsections.

3.01.2.2 Trends in Energy Demand for California

3.01.2.2.1 Introduction

Although long-term temperature trends have been studied across dozens of sites in California (Franco 2005; Lebassi et al.

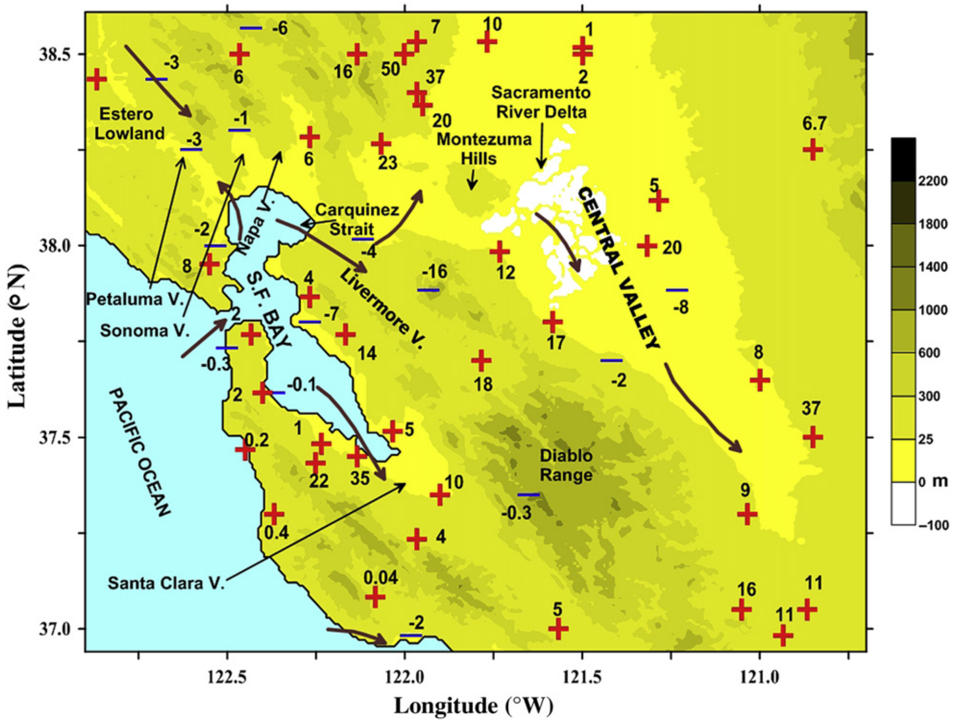

Latitude (°N)
Longitude (°W)
38.5
38.0
37.5
37.0
122.5
122.0
121.5
121.0
Estero Lowland
Sacramento River Delta
Montezuma Hills
Carquinez Strait
Napa V.
S.F. BAY
Livermore V.
CENTRAL VALLEY
Petaluma V.
Sonoma V.
PACIFIC OCEAN
Diablo Range
Santa Clara V.
-6
-3
6
16
50
7
37
10
1
2
20
-1
-3
6
23
6.7
5
-2
8
-4
12
20
-8
4
-7
-16
17
2
14
18
-2
8
-0.3
-0.1
2
37
1
5
0.2
22
35
10
9
-0.3
0.4
4
0.04
-2
5
16
11
11
2200
1800
1400
1000
600
300
25
0 m
–100

Figure 7 Spatial distributions of 1970–2005 summer CDD trends (DD decade^{-1}, where red pluses show increasing values and blue dashes show decreasing values) for the SFBA (Lebassi et al. 2010).

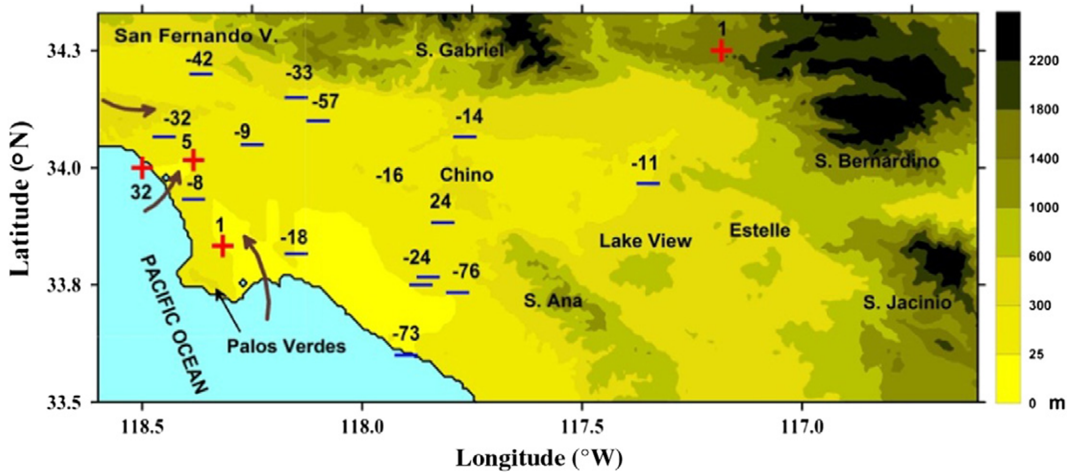

Latitude (°N)
Longitude (°W)
34.3
34.0
33.8
33.5
118.5
118.0
117.5
117.0
San Fernando V.
S. Gabriel
S. Bernardino
Chino
Lake View
Estelle
S. Ana
S. Jacinio
Palos Verdes
PACIFIC OCEAN
-42
-33
-57
1
-32
5
-9
-14
32
-8
-16
-11
24
1
-18
-24
-76
-73
2200
1800
1400
1000
600
300
25
0 m

Figure 8 Same as **Figure 6**, but for winter HDD trends (Lebassi et al. 2010).

2009, 2010; LaDochy et al. 2007; Cordero et al. 2011), actual energy demand studies have been restricted by short-term (Aroonruengsawat and Auffhammer 2009) and site-specific data availability (Miller et al. 2008; Franco and Sanstad 2008; Sequera et al. 2011). In order to ascertain long-term energy consumption trends across California, an analysis was undertaken using county-level monthly and yearly data from the California Energy Commission (CEC). These data were used to analyze spatial and temporal trends. Given the importance of understanding temperature–energy relationships in the context of global warming, this section focuses on actual energy consumption trends in coastal and inland California. An understanding of energy consumption behaviors at this spatial scale is important because statewide energy demands can be influenced by high population densities along the California coast, as shown in Figure 12 (U.S. Census Bureau 2011). Simple plots show that electric power consumption per person peaks during the summer time for coastal counties, inland counties, Sacramento County (located inland), and San Diego County, located along the coast. Moreover, the data show that electric power consumption per person appeared to increase from 1990 to 2009 for most

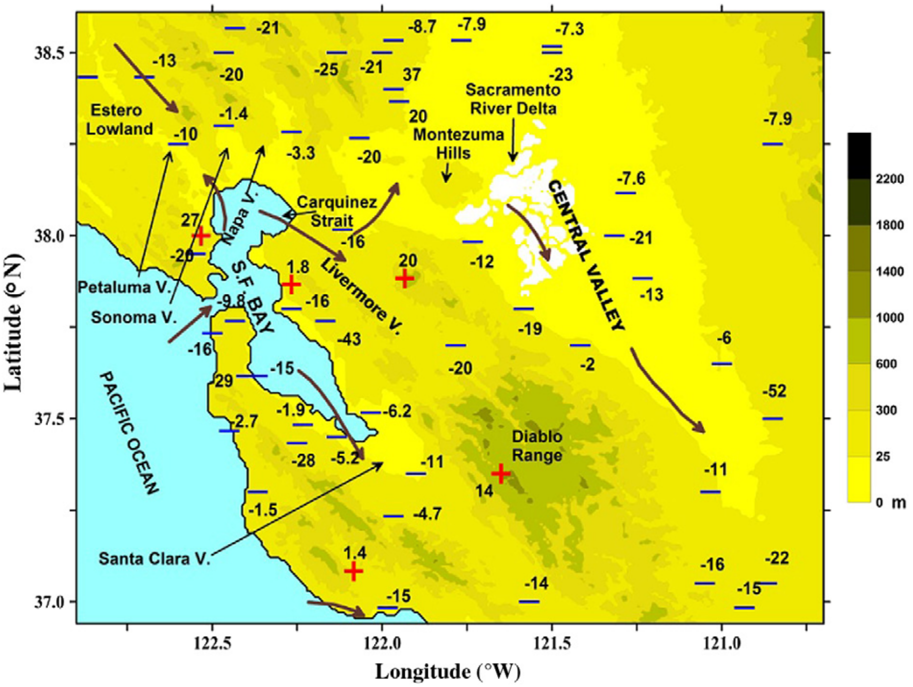

Latitude (°N)
Longitude (°W)
38.5
38.0
37.5
37.0
122.5
122.0
121.5
121.0
2200
1800
1400
1000
600
300
25
0 m
Estero Lowland
Petaluma V.
Sonoma V.
Napa V.
S.F. BAY
Carquinez Strait
Livermore V.
Sacramento River Delta
Montezuma Hills
CENTRAL VALLEY
Diablo Range
Santa Clara V.
PACIFIC OCEAN
-21
-8.7
-7.9
-7.3
-13
-20
-25
-21
37
-23
-1.4
20
-7.9
-10
-3.3
-20
-7.6
27
-16
-21
-20
1.8
20
-12
-13
-9.8
-16
-19
-43
-6
-16
-20
-2
29
-15
-52
-6.2
-1.9
2.7
-28
-5.2
-11
-11
14
-1.5
-4.7
1.4
-16
-22
-15
-14
-15

Figure 9 Same as Figure 7, but for winter HDD trends (Lebassi et al. 2010).

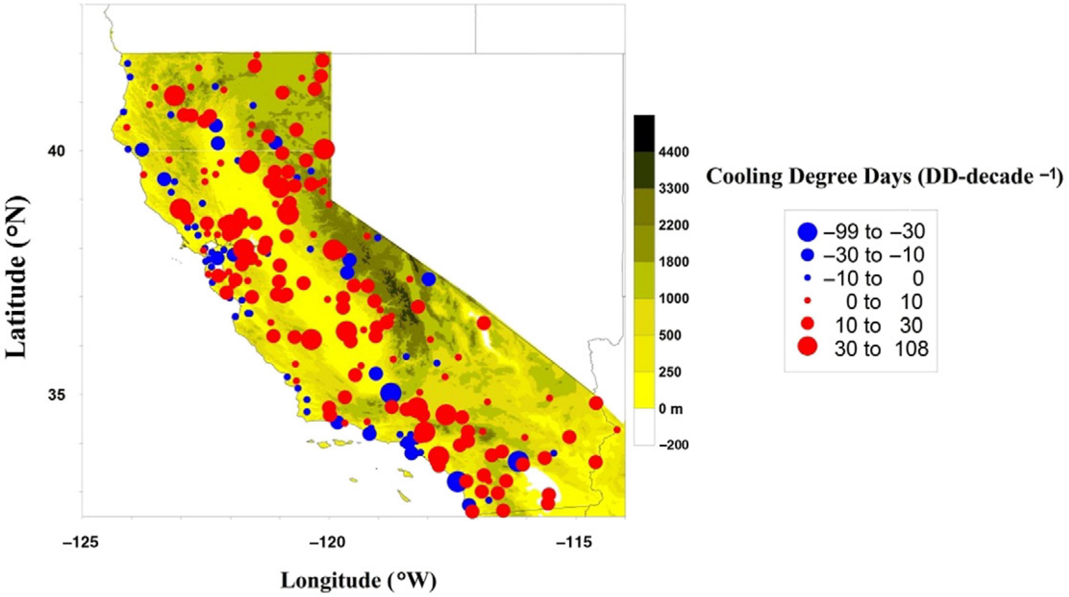

Latitude (°N)
Longitude (°W)
40
35
−125
−120
−115
4400
3300
2200
1800
1000
500
250
0 m
−200
Cooling Degree Days (DD-decade −1)
● −99 to −30
● −30 to −10
• −10 to 0
• 0 to 10
● 10 to 30
● 30 to 108

Figure 10 Spatial distribution of maximum monthly summer CDD trends. Red symbols represent heating sites and blue symbols represent cooling sites. Elevation in meters, blue points represent cooling trends while red points represent heating trends. Size of the symbol indicates absolute value of the trend.

counties. In contrast, the data show that natural gas consumption per person appeared to decrease from 1990 to 2009 for most counties.

3.01.2.2.2 Data and Methods

County-level energy consumption data were obtained from the CEC. Electric power and natural gas consumption data were available for two temporal scales, monthly and yearly. Monthly data consisted of energy consumption estimates from 2005 to 2007. Yearly data consisted of residential and nonresidential energy actual consumption from 1990 to 2009. Both monthly and yearly residential electric power and natural gas values were normalized by population figures (U.S. Census Bureau 2011).

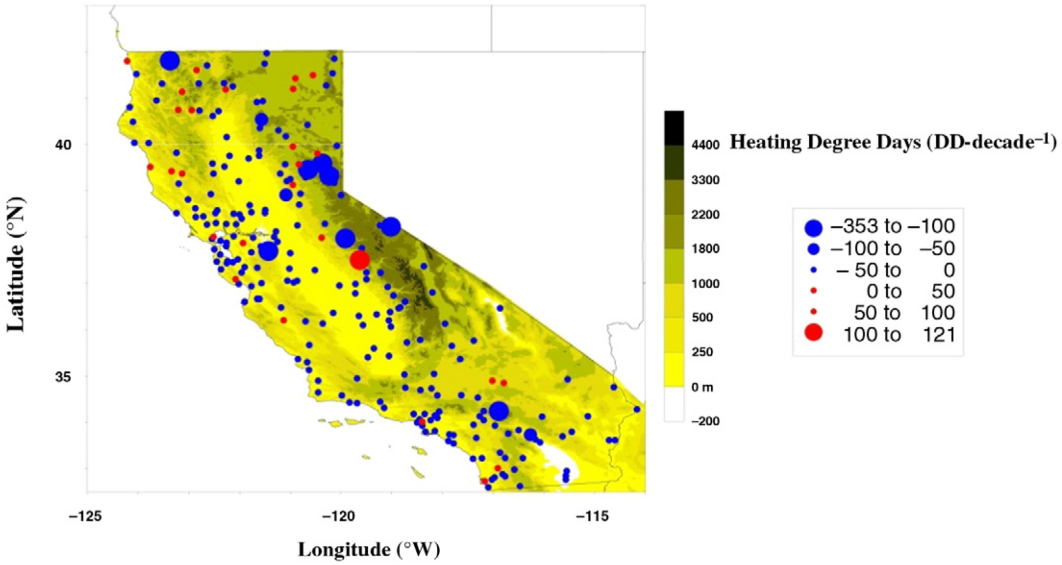

Heating Degree Days (DD-decade⁻¹)
4400
3300
2200
1800
1000
500
250
0 m
−200
−353 to −100
−100 to −50
− 50 to 0
0 to 50
50 to 100
100 to 121
Latitude (°N)
40
35
−125
−120
−115
Longitude (°W)

Figure 11 Spatial distribution of maximum monthly winter HDD trends. Red symbols represent increasing HDD sites and blue symbols represent decreasing HDD sites. Elevation in meters. Size of the symbol indicates higher absolute value of the trend.

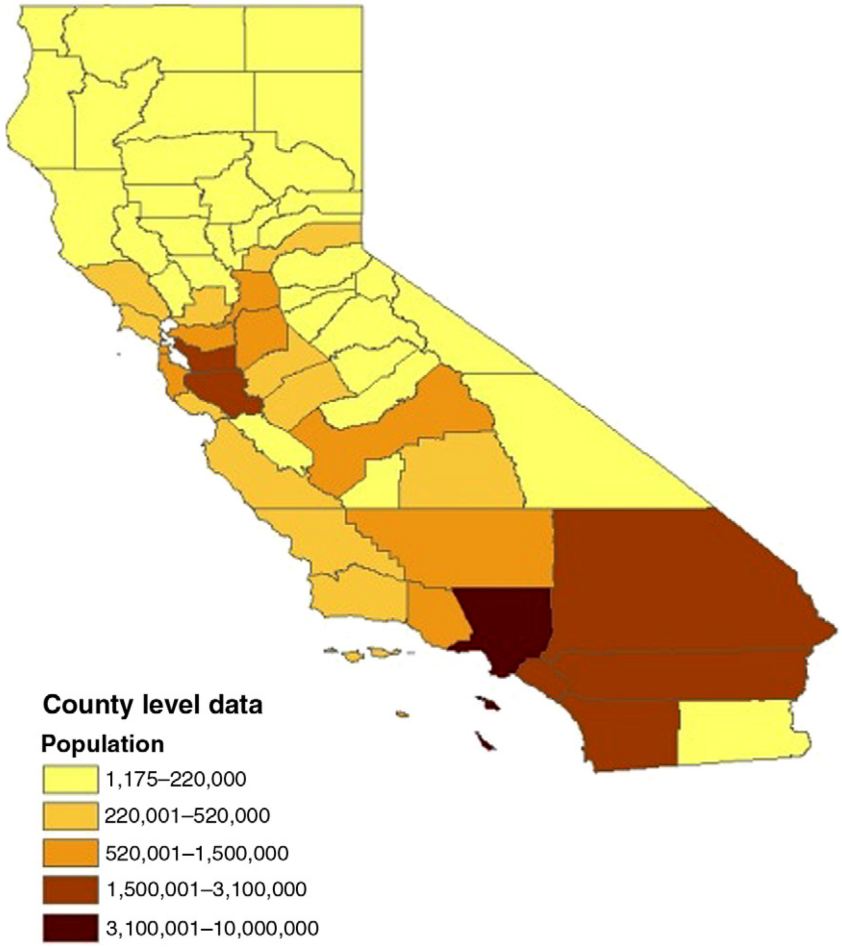

County level data
Population
1,175–220,000
220,001–520,000
520,001–1,500,000
1,500,001–3,100,000
3,100,001–10,000,000

Figure 12 California census 2010 population by county (U.S. Census Bureau 2011).

Data from the CEC were used to create several graphs and maps. First, for the electric power consumption analysis, counties were divided into two categories: coastal and inland. For simplification, coastal counties included those in the western boundary that met the Pacific Ocean. Therefore, out of 58 counties, 15 were considered coastal while 43 were considered inland. Graphs were created using monthly average estimates with 2005–2007 values; inland minus coastal difference in monthly average estimates; and yearly residential actuals from 1990 to 2009. Finally, county-level maps were created using linear regression values for electric power consumption from 1990 to 2009.

Similarly, the natural gas consumption analysis per county was divided into coastal and inland counties. Unfortunately, natural gas consumption data were not available for all counties, specifically Alpine, Del Norte, Inyo, Lake, Lassen, Mariposa, Modoc, Mono, Plumas, Sierra, Siskiyou, and Tuolumne. However, these counties represent less than 1% of the total California population from 1990 to 2009 (U.S. Census Bureau 2011). Therefore, exclusion of these natural gas consumption values should not significantly impact the analyses presented in this section. As a result, out of 46 counties with available data, 14 were considered coastal while 32 were considered inland. Graphs were created using yearly residential actuals from 1990 to 2009. Afterward, county-level maps were created using linear regression values for natural gas consumption from 1990 to 2009.

3.01.2.2.3 Results for Trends in Energy Demand for California

Electric power

Figure 13 shows plots of average monthly electric power consumption for inland counties, coastal counties, Sacramento County, and San Diego County. Such plots show the seasonal variation of energy consumption. For example, consumption for included regions increases during the summer months from May to August and generally decreases from August to April. Peak electric power consumption appears to occur in August, at which point consumption peaks at about 590 kWh per person for coastal counties and 980 kWh per person for inland counties. A possible explanation for this trend may be an increased need for space cooling, such as air-conditioning, during the summer months. Numerous studies have shown strong correlations between temperature (or heating degree days) and energy demands during summer (winter) months (Miller et al. 2008; Franco 2005; Lebassi et al. 2010; Crowley and Joutz 2005; Fung et al. 2006; Lam 1998; Le Comte and Warren 1981; Warren and LeDuc 1981; Bartholomew et al. 2002).

Interestingly, as shown in **Figure 14**, the difference between inland and coastal counties average monthly electric power consumption also appears to peak during the summer time, at 400 kWh in August. This difference in electric power consumption is consistent with recent findings previously discussed that show increasing summer temperatures in inland areas and decreasing summer temperatures in coastal areas (Lebassi et al. 2009, 2010; Sequera et al. 2011). In addition, this trend may also be affected by temperature-dependent energy demand responses within each building climate zones. For example, a recent study for California found that the energy demands of residents in some inland building climatic zones change more rapidly at higher temperatures when compared to coastal building climatic zones (Aroonruengsawat and Auffhammer 2009).

It should be noted that it appears that December electric power consumption is the highest value for both inland and coastal counties. However, it is likely that these data values result from the process by which CEC accepts electric power consumption data from energy providers, namely that adjustments can be made to previously submitted reports. These adjustments can be added to the month of December. As a result, December electric power consumption values should be disregarded.

At the yearly temporal scale, trends in energy consumption can be attributed to economic, social, and demographic factors (Lam 1998) in addition to climate responses. **Figure 15** shows yearly residential electric power consumption for the coastal

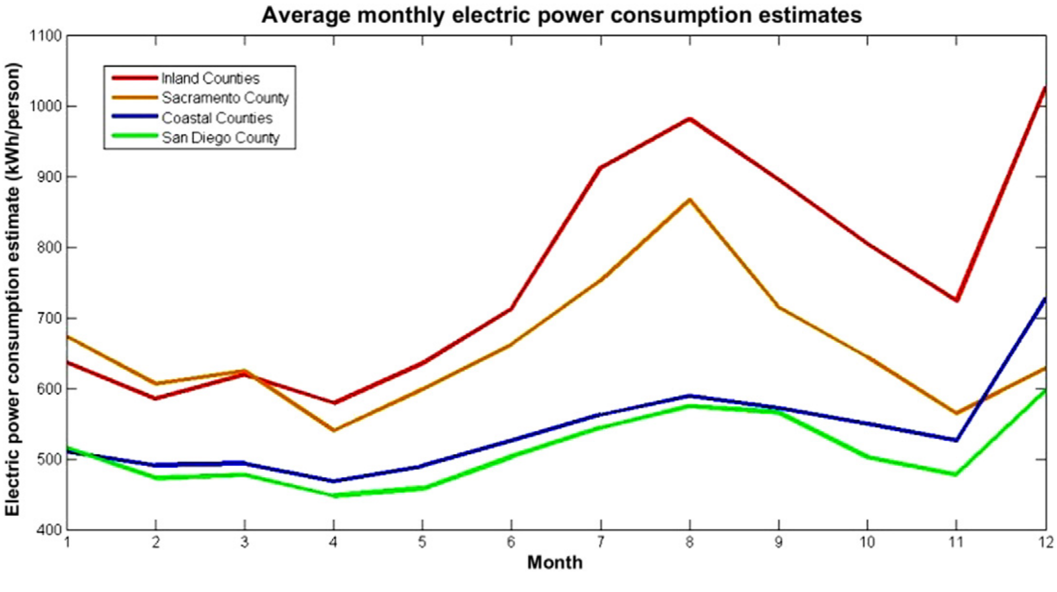


Figure 13 Average monthly electric power consumption estimates for inland counties, coastal counties, Sacramento County, and San Diego County.

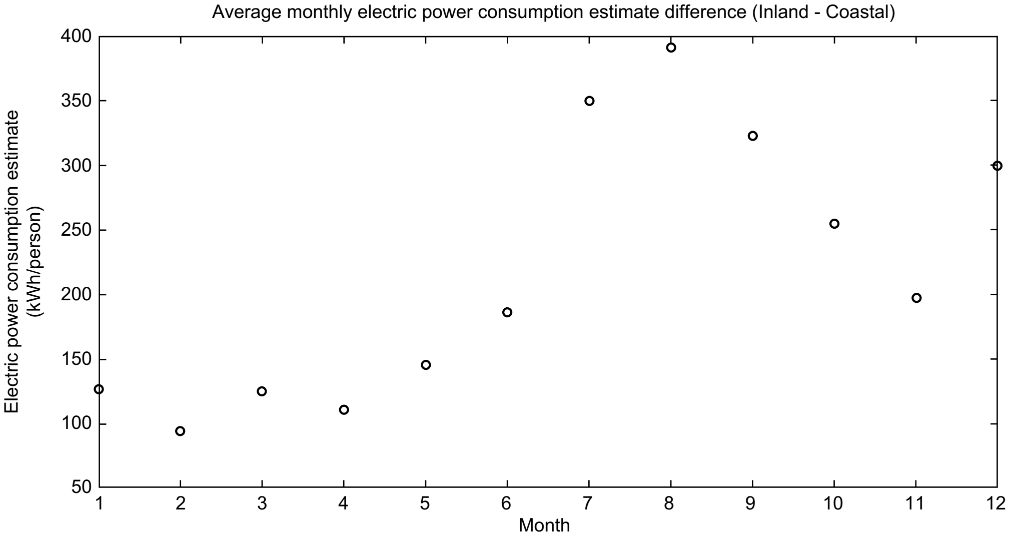


Figure 14 Average monthly electric power consumption (inland minus coastal).

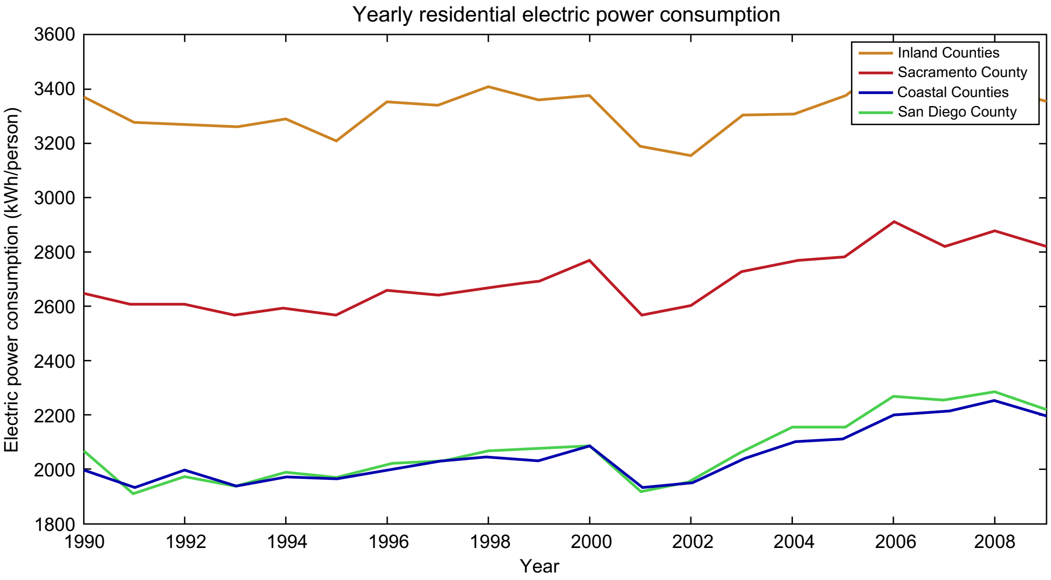


Figure 15 Yearly residential electric power consumption for inland counties, coastal counties, Sacramento County, and San Diego County.

and inland counties of San Diego and Sacramento. These areas exhibited similar increasing and decreasing patterns. Overall, electric power consumption increased from 1990 to 2009 in such areas. For example, coastal county consumption increased by 10% during this time, from about 2000 to 2200 kWh per person. Similarly, inland county consumption increased by 8%, from about 2600 to 2800 kWh per person.

In addition to the overall increasing trend from 1990 to 2009, all regions show noticeable decreases in electric power consumption in 2001. This decrease is probably attributed to increased consumer conservation and energy efficiency measures introduced in 2001 after major power outages in 2000 throughout the state (Lebassi et al. 2009). Afterward, electric power consumption appears to increase from 2001 to 2009.

Coastal county consumption is lower than inland county consumption for all years. These results are consistent with residential electric power consumption billing data obtained by the CEC (Aroonruengsawat and Auffhammer 2009). Residential billing data from 2003 to 2006 were sampled and aggregated for 16 building climate zones. As shown in Figure 16 (CEC 2011), coastal building climate zones include Zones 1, 3, 5, 6, and 7. All other zones represent inland building climate zones. The mean electric power consumption per billing cycle for coastal building climate zones was between 469 and 550 kWh per household. In contrast, the mean electric power consumption per billing cycle for inland building climate zones was between 583 and 795 kWh per household. It is possible that building climate zone, which have different

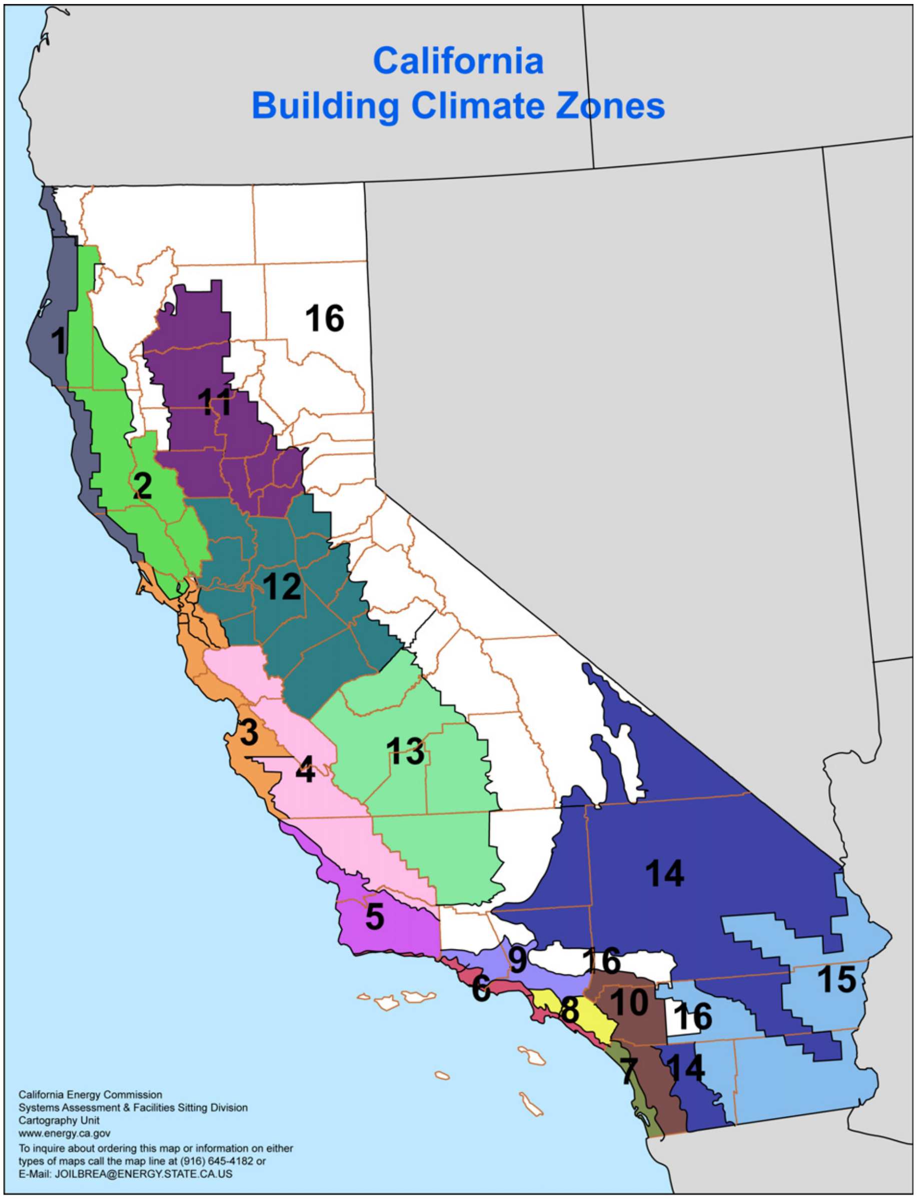

California
Building Climate Zones
16
1
11
2
12
3
4
13
14
5
9
16
6
15
8
10
16
7
14
California Energy Commission
Systems Assessment & Facilities Sitting Division
Cartography Unit
www.energy.ca.gov
To inquire about ordering this map or information on either
types of maps call the map line at (916) 645-4182 or
E-Mail: JOILBREA@ENERGY.STATE.CA.US

Figure 16 California building climate zones (California Energy Commission, 2011).

building standards, play a role in electric power consumed per household.

Figure 17 shows a map of California county-level residential electric power consumption per person per year. Counties with a positive increase in electric power consumption are shown in a range of yellow to red, with red representing the highest values. In contrast, counties with decreasing electric power consumption per person per year are shown in a range of greens, with dark green representing the highest values. It appears that, on a county-level, electric power consumption is increasing for almost all counties except three, Mono, Madera, and Stanislaus. This finding is generally consistent with the yearly analysis conducted for inland and coastal counties showing increased electric power consumption from 1990 to 2009 (Figure 15).

Natural gas

Similar to electric power consumption, natural gas consumption at the yearly temporal scale can be evaluated in the context of economic, social, demographic, and climate factors (Lam 1998). Figure 18 shows yearly residential natural gas consumption for coastal counties, inland counties, Sacramento County, and San Diego County. In general, natural gas consumption decreased from 1990 to 2009 in the included regions. In particular, coastal county consumption decreased by 22% during this time, from about 5100 to 4000 kWh per person. Similarly, inland county consumption decreased by 23%, from about 5200 KWh per person to 4000 kWh per person.

The decreasing trend in natural gas consumption is consistent with the decreasing HDD; however, other factors could be contributing including increases in natural gas prices, the

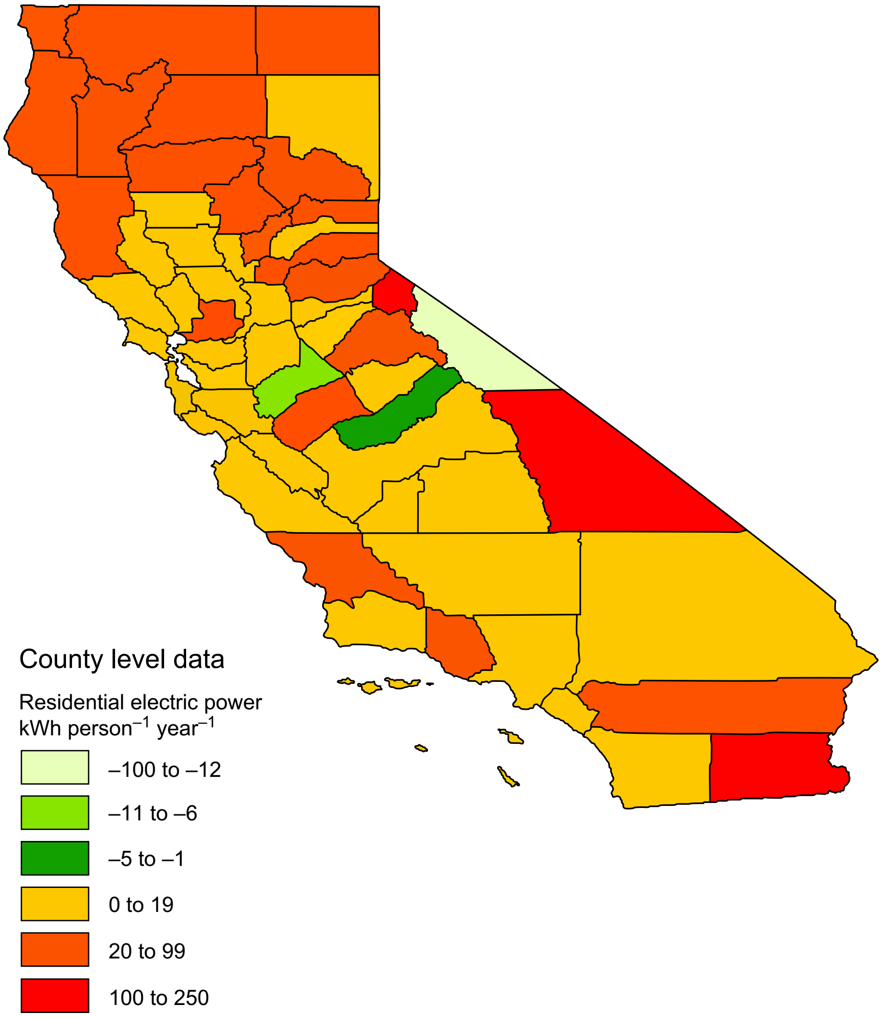

County level data
Residential electric power
kWh person⁻¹ year⁻¹
–100 to –12
–11 to –6
–5 to –1
0 to 19
20 to 99
100 to 250

Figure 17 California 1990–2009 residential electric power consumption per person per year.

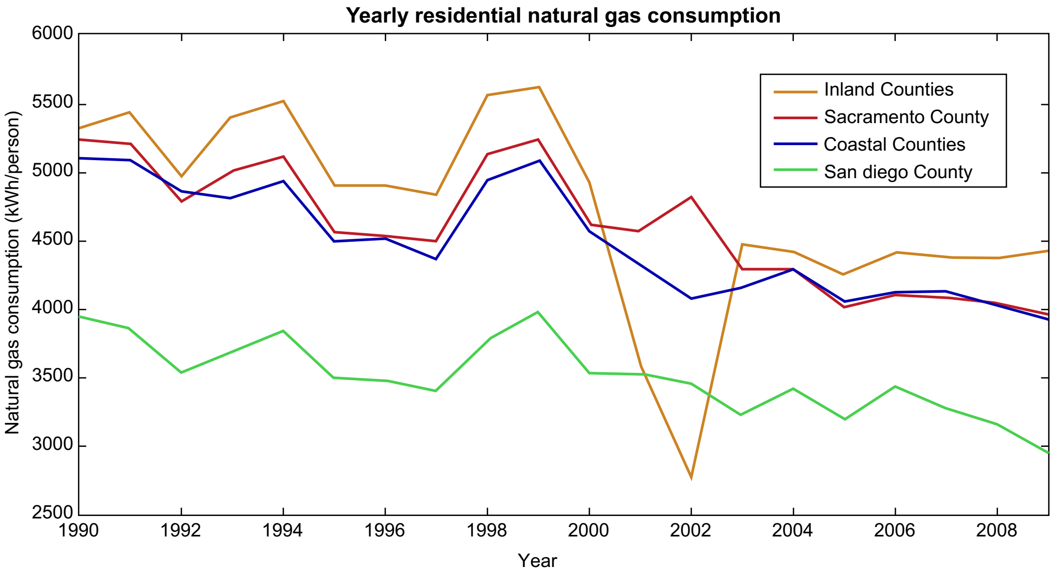


Figure 18 Yearly residential natural gas consumption for inland counties, coastal counties, Sacramento County, and San Diego County.

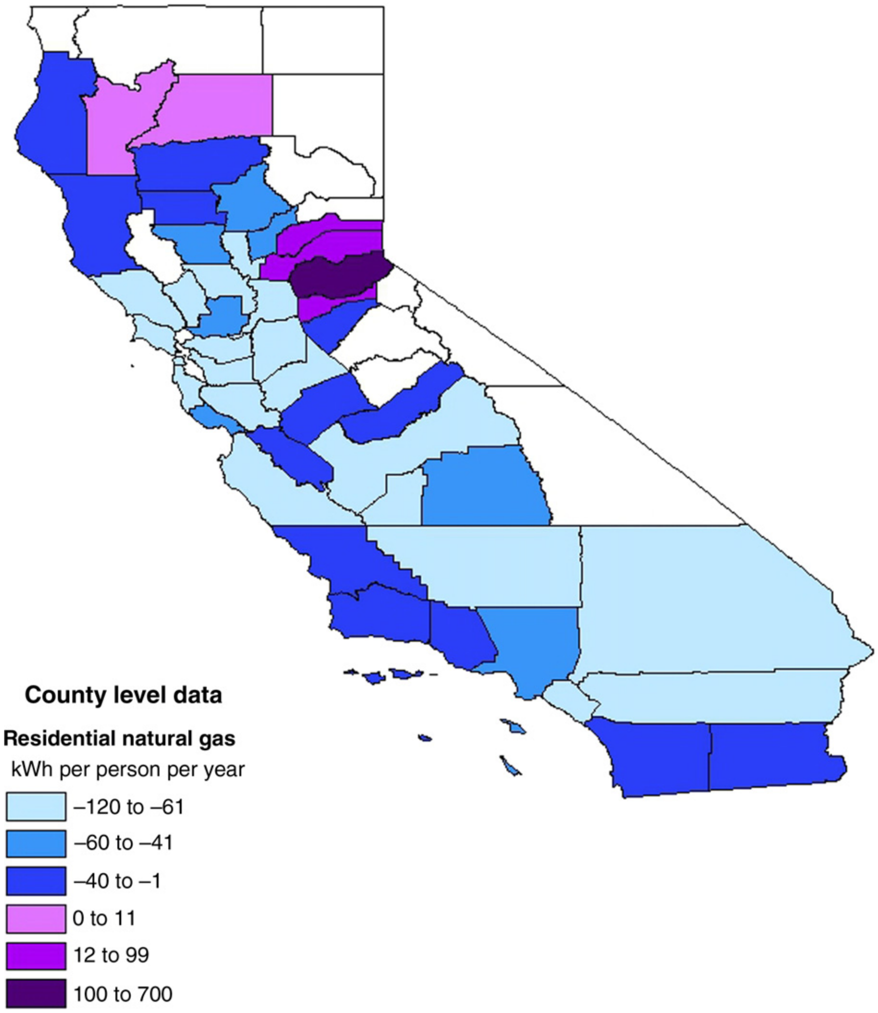


Figure 19 California 1990–2009 residential natural gas consumption per person per year.

availability of energy efficient space-heating equipment, and the use of alternative forms of energy for heating (Trends in Residential Natural Gas Consumption 2011). Moreover, the major factor influencing this trend may be the warming of temperatures during the winter time throughout California, which may lead to decreased natural gas consumption for space-heating as previously discussed (Lebassi et al. 2010).

Figure 19 shows a map of California county-level residential natural gas consumption per person per year. Counties with a positive natural consumption are shown in a range of purples, with dark purple representing the highest values. In contrast, counties with negative natural gas consumption per person per year are shown in a range of blues, with dark blue representing the highest values. It appears that on a county level, natural gas consumption is decreasing for almost all counties except six, Amador, El Dorado, Nevada, Placer, Shasta, and Trinity. This finding is generally consistent with the yearly analysis conducted for inland and coastal counties showing decreasing natural gas consumption from 1990 to 2009.

Energy analysis for the commercial and industrial sector shows less sensitivity to the climate trends of axysymmetric warming in California. Figures 20 and 21 show the aggregated electric power consumption for the industrial and commercial sector in California, excluding transportation. It can be noted that there are no significant differences between inland and coastal regions. This is clear evidence that industrial and commercial activity are driven by demands for production and consumer habits (sales), rather than responses to local weather conditions and climate trends.

Peak energy demand

Peak June, July, and August (JJA) electricity-usage trends were calculated for five California utilities for which such data were available, i.e., Sacramento Municipality Utility District, Santa Clara, Los Angeles Department of Water and Power (LDWP), Pasadena, and Riverside; the first two are in the SFBA, while the last three are in the SoCAB. Peak usage was normalized by the 1993–2004 population trends for each location. The SoCAB results (Figure 22(a)) showed coastal LDWP with the largest decrease (-0.17 kW decade^{-1} person^{-1}), consistent with its coastal marine-influenced decreased JJA CDD values of Figures 6 and 7. Midway-inland Pasadena showed only

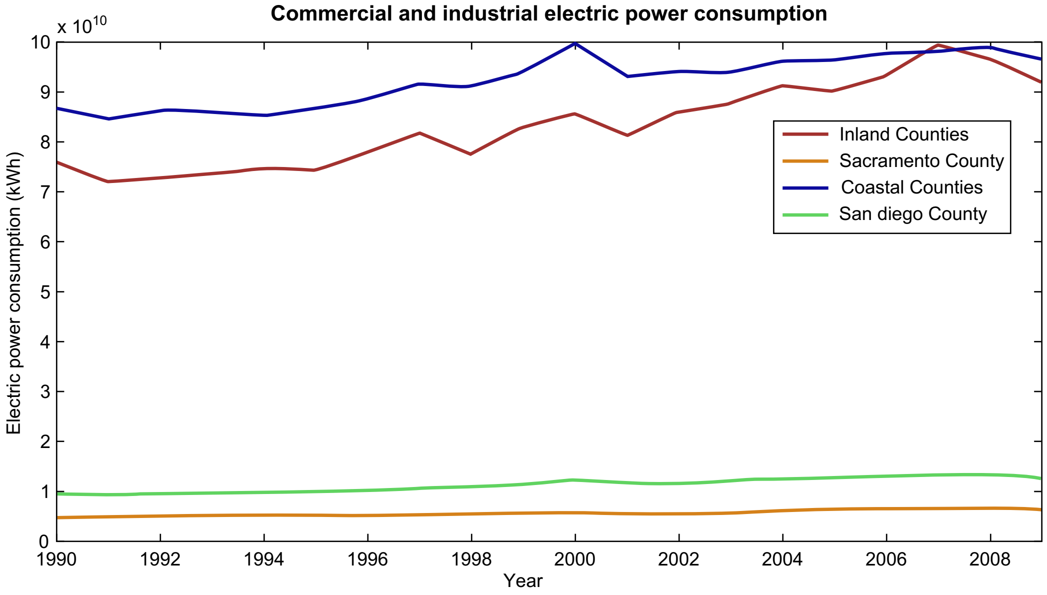


Figure 20 Yearly commercial and industrial electric power consumption for inland counties, coastal counties, Sacramento County, and San Diego County.

a small decrease (-0.01 kW decade^{-1} person^{-1}), even though its CDD trend showed a small increase. Inland Riverside had the largest increase (0.18 kW person^{-1} decade^{-1}), consistent with its inland global warming dominated increased CDDs. These peak energy-demand results are again consistent with the $T_{\max}$ results of Lebassi et al. (2009) as the peak electricity usage is associated with air conditioning usage for summer cooling. The SFBA sites of Sacramento and Santa Clara (Figure 22(b)) show increasing JJA CDD trends of 0.33 and 0.45 kW decade^{-1} person^{-1}, respectively, consistent with both their $T_{\max}$ (Lebassi et al. 2009) and CDD increases in Figures 6 and 7 but inconsistent with their inland distances. A comparable December, January, and February (DJF) analysis was not carried out, as almost all sites would show decreased HDD values and because California gas usage is minimal in summer.

California utilities for which annual natural gas data were available included Pacific Gas and Electricity, Southern California Gas Co., City of Palo Alto Gas Co., and Long Beach Gas Co. The first two are SFBA and SoCAB regional utilities, respectively, while the next two are an SFBA and a SoCAB local city utility, respectively; natural gas usage was not normalized by population trend. Annual natural gas usage for 1990 to 2007 in all four areas decreased as expected (Figure 23) due to GHG warming, with a range of values from (-5×10^6) to (-45×10^6) therms decade^{-1}. These decreasing values are consistent with the generally deceasing HDD values in Figures 8 and 9 due to GHG warming, as natural gas is mainly used for winter space heating. Although Figure 23 showed only the total utility usage, per capita values must also be downward, given the increased populations in those areas during the period of the study. The documented decreases in peak cooling and warming energy demands may also be due in some part to increased energy efficiencies.

3.01.2.2.4 Concluding Remarks on Energy Analysis for California

The analysis of California's county-level energy consumption shows similarities and differences between coastal and inland areas. First, in terms of similarities, monthly electric power consumption shows peaks during the summer time. These findings at the monthly temporal scale are suggestive of an increased need for electric power for space cooling during summer. Second, trends for inland and coastal counties peak electric power consumption show increases for inland areas and decreases for coastal areas from 1990 to 2009. Third, in terms of similarities, both inland and coastal areas show decreases in natural gas consumption. Such findings may be explained by increases in natural gas prices, the availability of energy efficient space-heating equipment, and the use of alternative forms of energy for heating. However, the correlation with climate trends is evident when compared with the surface temperature analysis (see Section 3.01.4.1 Surface Temperature Trends in California). It was shown that natural gas usage has a uniform decreasing pattern, attributed to warmer winters.

3.01.2.3 Energy Trend Forecast in California

There are many challenges to predicting electricity consumption trends since there are many factors that could play a major role in the regional consumption variability for the future. These factors could include climatic trends, electric power system details, socioeconomic trends, economic growth and technological change, demographic trends, and the effect of public policies. All these variables are very difficult to predict not only in the long range but also for a short period.

Franco and Sanstad (2008) analyzed the impact of temperature changes on summer electricity demand and peak loads using hourly electricity consumption data in the California Independent System Operator (CalISO) area. They found a very

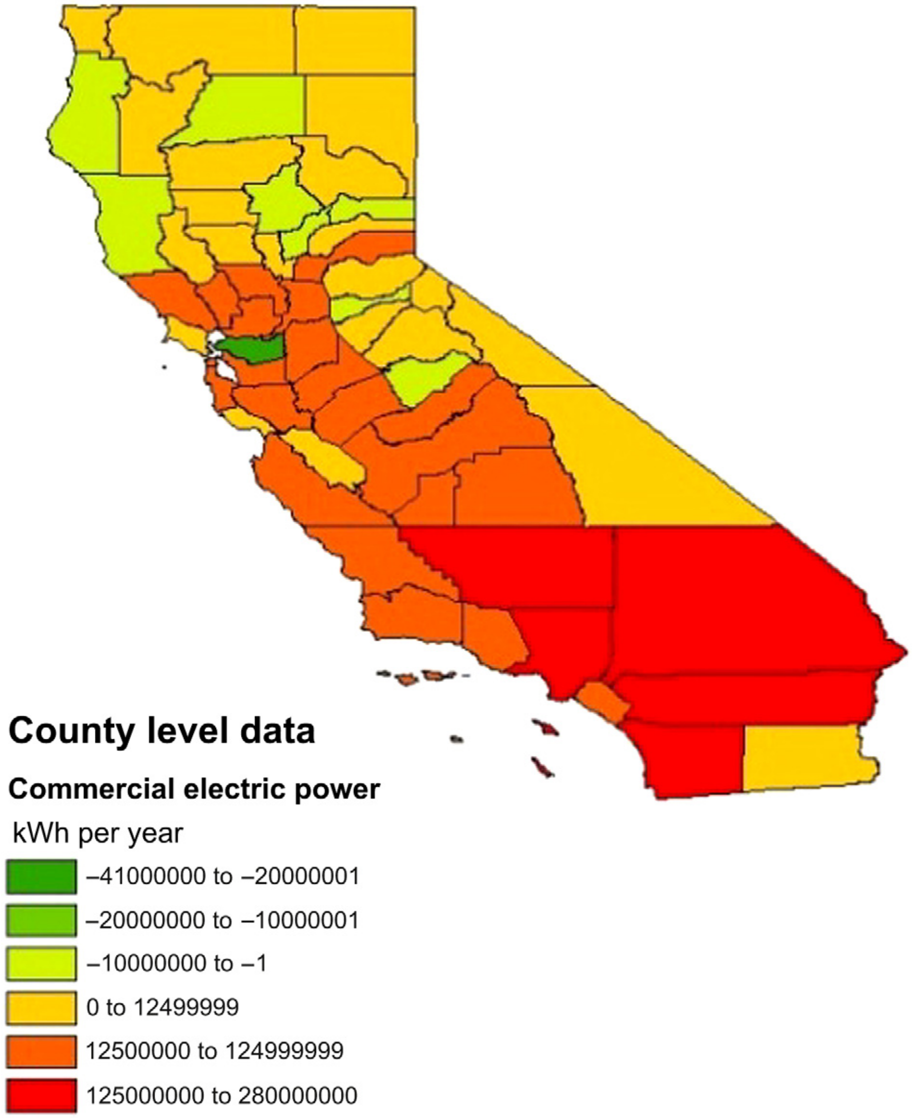


Figure 21 California 1990–2009 commercial and industrial electric power consumption per year.

high correlation ($R^2 > 0.9$) between the simple average daily temperature and daily electricity demand in the CalISO region using a cubic polynomial. The authors' interpretation of this curve was that at low temperatures, temperature increases initially result in a reduction of electric space heating and to some extent a reduction in the use of indoor appliances, the utilization of which increases during cooler weather. While at higher temperatures, the effects of space cooling via air conditioners and the uses of other appliances predominate. They also reported a high correlation ($R^2 > 0.8$) between hourly peak electricity demand in the CalISO region and the hourly maximum temperature in four locations from 2004 to 2005.

In this work, electricity consumption trends are projected into the future using the relationships derived from Franco and Sanstad (2008) as an approximation along with forecasted temperature trends from CMIP3 models (see Section 3.01.4.3), under exactly the same assumptions used by others, e.g., the underlying relationships between temperature and consumption and maximum temperature and peak demand remain invariant. Also, the equation used by Franco and Sandstad uses average daily temperature as the independent variable, so there is some bias introduced in the estimations since we used period trends for average monthly temperature. The forecast is predicted for two periods: 2011–40 and 2041–70.

As expected, annual California electricity demand shows a slight increase in all cases (Table 1) with a higher increase using the A2 scenarios (see Section 3.01.4.3). For the 2011–40 period, the A2 scenario predicts a 3.713% increase in annual electricity consumption while the B1 scenario predicts a 2.172% increase. The increase is more obvious in the 2041–70 period where the A2 scenario forecasts a 7.185% increase and the B1 scenario shows an increment of 4.683% in annual electricity consumption. Even though the projected annual electricity demand increase percentage is not very high for any of the periods or scenarios, even small percentage increases in energy demand would substantially raise energy-related expenditures (Miller et al. 2008).

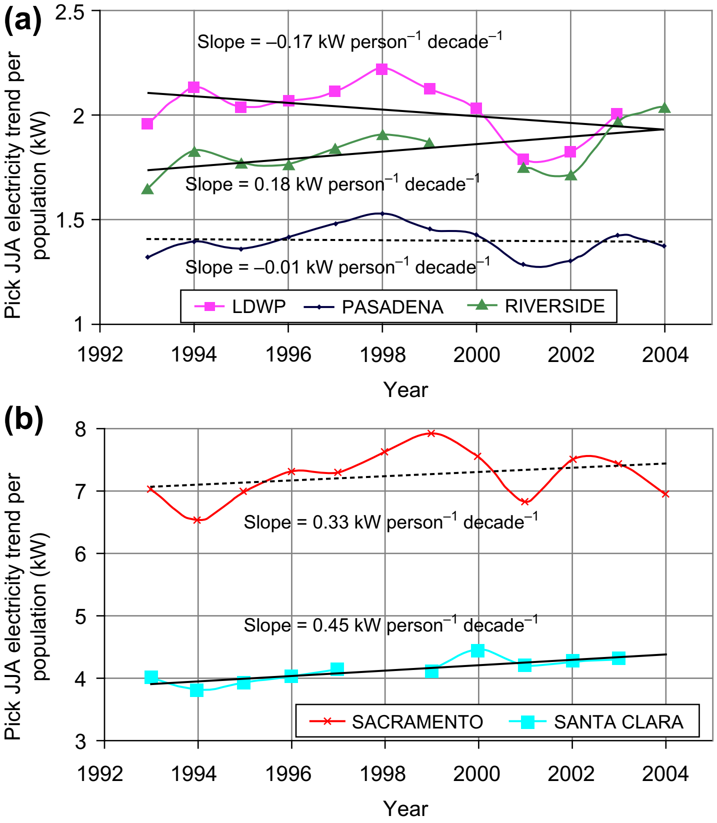


Figure 22 Trends in peak summer electricity usage at locations in (a) SoCAB and (b) SFBA (Lebassi et al. 2010).

3.01.3 Energy Demand Trends in the Northeast Corridor

This work has been extended to include connections between energy and climate for the Northeast Corridor (NEC) of the United States. An analysis of climatology, power consumption, and emissions was made for this region following the methodology used for California. This region represents approximately 4% of total power consumption in the United States. For the purpose of the energy analysis, the states that define the NEC region are Pennsylvania, New Jersey, New York, Vermont, Connecticut, Massachusetts, Delaware, New Hampshire, Maine, and the District of Columbia. State energy profiles were compiled from the U.S. Energy Information Administration (EIA) (Dzioubinski et al. 1999). Utilizing the state's energy data system from EIA, energy consumption figures were analyzed from 1960 to 2009. Residential and nonresidential sectors are presented to show the main trends within each state. In regard to the nonresidential sector, the commercial and industrial sectors are joined together to comprise the nonresidential sector. To understand the long-term energy consumption trends in the NEC, the Energy Information Administration section on State Energy System were utilized to produce a dataset that aggregated energy totals for each of the 9 states, in addition to the District of Columbia (Energy Information Administration 2011). Total sector energy data were aggregated by kilowatt hours for coal, natural gas, residential fuel, distillate fuel, kerosene, motor gasoline, and liquid petroleum gasoline. Furthermore, the data were spatially aggregated so it could be utilized to provide insights about the interaction with energy emissions and the climate.

To understand greenhouse emissions trends, historical population and urban density have to be analyzed. The United Nations Centre for Human Settlements has reported that cities account for producing the largest slice of greenhouse emissions with estimates as high as 80% for the world (Dodman 2009). It is estimated that about 43% of US. carbon emissions are produced from residential, commercial, and industrial building, and the US NEC is a highly urbanized region (Energy Information Administration 2011). According to the US Census Bureau, the Northeast is expected to expand to one-half of the US total rate by 2025 (U.S. Census Bureau 2011). The region will approximately add about six million inhabitants by 2025; this trend is a reduced one in comparison with 1995–2000. Further, the Northeast region contains five major urban centers: Boston, New York, Philadelphia, Baltimore, and Washington DC.

According to the Northeast Data Abstract of EIA in 1997, the Northeast has an estimated 20 million households compared to the total 102 million of the United States. Household energy consumption represents about 2.4 quadrillion BTU out of the 10 quadrillion consumed by the United States. This represents one of highest household energy consumption in the world (Dzioubinski et al. 1999).

For the NEC, the residential sector shows a dramatic decrease in energy consumption. In Figure 24, for 1960, the

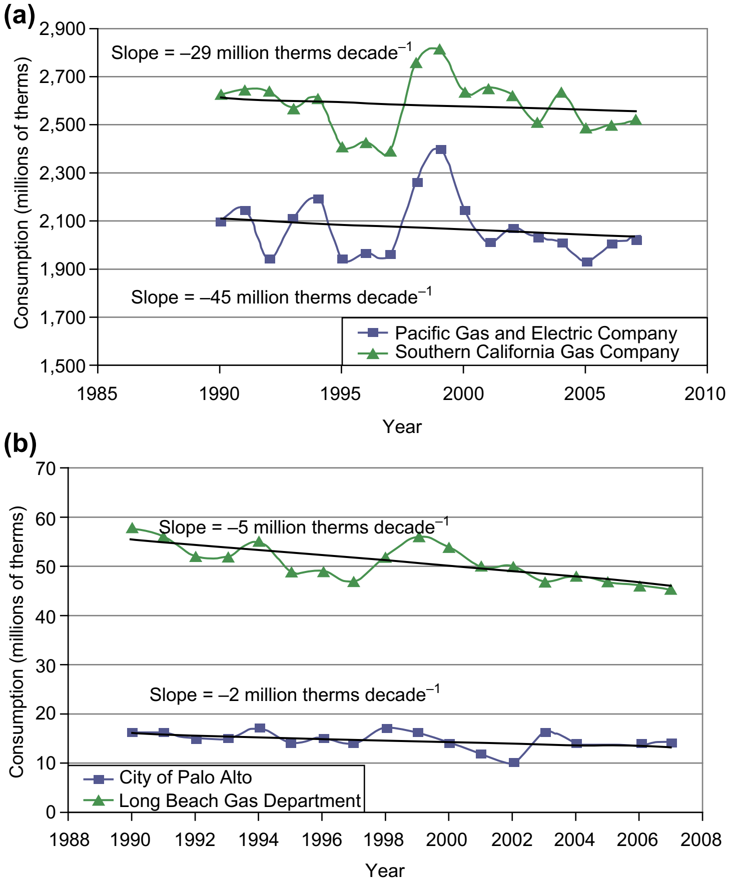


Figure 23 Trends in peak winter gas usage at selected locations (Lebassi et al. 2010).

data indicate that per capita the residential sector of the Northeast region annually consumed 14 000 kWh per person, reflecting a peak by the mid-1970s. By the year 2009, the number had substantially decreased down to 10 000 kWh per person or a 37% change. The substantial decrease over a period of four decades can be attributed mostly to increased energy efficiencies in buildings, and may be due to a warming climate reflected mostly in warmer winters.

Data also suggest that nonresidential energy consumption rapidly rose since 1960 with a maximum in the 1970s (see Figure 25). The years proceeding depict a sharp decline in nonresidential energy consumption. A number of factors have contributed to the decline such as urbanization, which determines fuel type usage, energy efficiency, and stronger environmental legislations that were enacted, such as the National Environmental Policy Act in 1970. Figure 25 clearly shows that over a period of time there has been a change in nonresidential fuel usage. In 1960, coal usage composed a significant slice of energy consumption. After 1981, a substantial decrease occurred while natural gas energy consumption rose during that same period of time. Natural gas is a cleaner burning fossil fuel than coal. Coal is one of the primary contributors of greenhouse emissions.

Table 1 Estimated changes in annual California electricity demands for different scenarios

Period	*Scenario*	*Increase in annual electricity consumption (%)*
2011–40	A2	3.713
2011–40	B1	2.172
2041–70	A2	7.185
2041–70	B1	4.683

At the sector level, CO_2 emissions associated to residential energy demand drastically decreased over 37% per capita, attributed to energy efficiencies and possibly to a warmer region in the winter. Despite these trends, the NEC region continues to be one of the largest CO_2 sources of the United States accounting for more than 15% of all emissions with an increasing trend. These results demonstrate the vulnerability of the region to climate changes and possible ways to mitigate impacts.

The residential sector represents a large portion of the regional energy budget, and it may be the most vulnerable of all sectors to a warming climate, particularly in summer. Expected mean increases may be mitigated by better energy technologies, as was shown in this analysis. This may differ for extreme summer events, such as heat waves, as was the case of California.

The data for the NEC also suggest that more warming is occurring along coastal areas versus inland temperatures (see

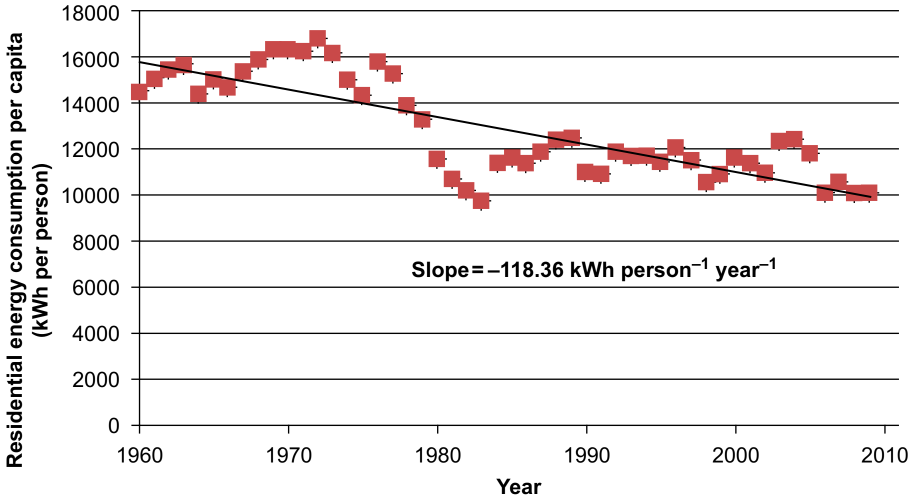


Figure 24 Total Northeast residential energy consumption per capita, 1960–2009.

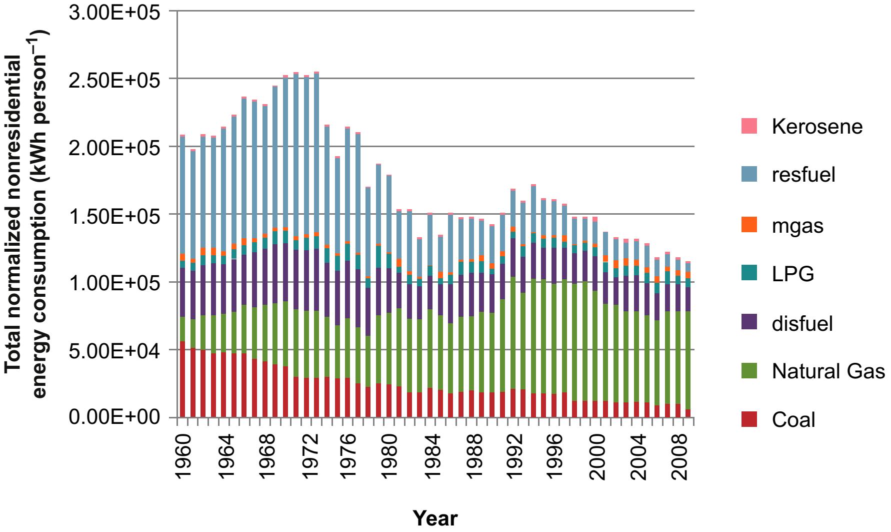


Figure 25 Total Northeast nonresidential energy consumption by fuel type per capita, 1960–2009.

Section 3.01.4.4 Climate Trends in the US Northeast Corridor). Several variables could contribute to the difference in warming. Most major cities lie along coastal areas, Boston, New York, Baltimore, and Washington D.C., contributing to higher levels of anthropogenic emissions and increased occurrence of the UHI effect. A second key variable is a warmer global climate that is reflected mostly in warmer Sea Surface Temperatures (SSTs). However, the total or relative contributions of these two variables (land use for urbanization and SSTs due to global warming) are not known for the NEC.

It can also be inferred that minimum temperatures are the key controlling variables in energy demands for this region, due mostly to the cooling trend. This is reflected in the larger decrease in natural gas (winter) over electricity (summer). The overall effect seems to indicate that under mean conditions, the energy sector may be less vulnerable to climate changes in these Northern regions.

3.01.4 Temperature Trends Analysis

3.01.4.1 Surface Temperature Trends in California

To better understand the temporal and spatial energy trends presented in the previous section, it is necessary to discuss the climatic trends. Many studies have confirmed that average California 2-m temperatures increased over the past decades. In particular, during the summer, these trends show diurnal asymmetric warming rates, where nighttime minimum temperatures ($T_{\min}$) have warmed faster than daytime maximum values ($T_{\max}$), thus decreasing the daily temperature range. The observed asymmetric warming during the last three decades at California coastal sites have been attributed to increases in cloud cover (Nemani et al. 2001), Sea Surface Temperatures (Goodridge 1991; Karl et al. 1993), upwelling (Bakun 1990; Snyder and et al. 2003; McGregor et al. 2007), land use changes for urbanization (Pielke et al. 2002; Chase

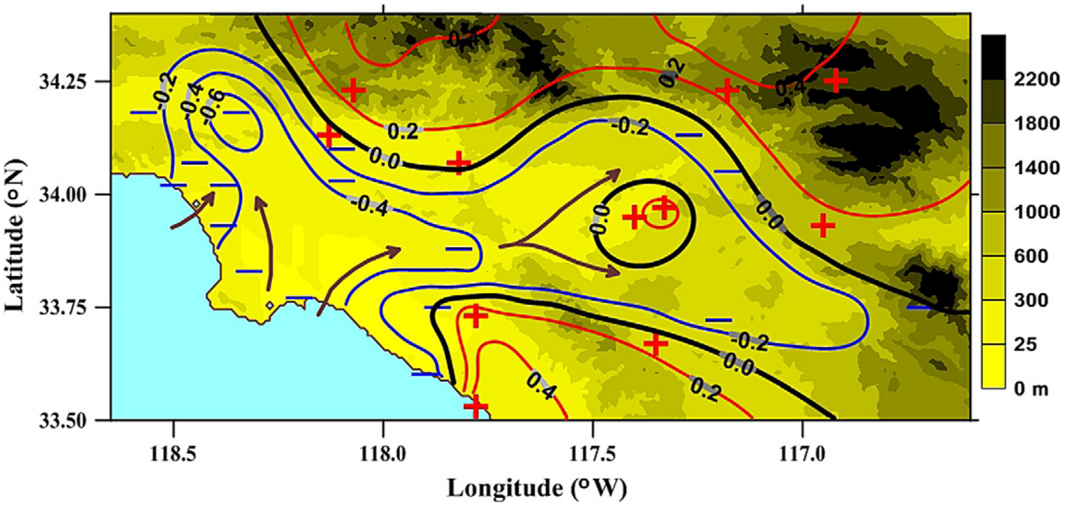


Figure 26 SoCAB 2-m summertime maximum-temperature trends (°C decade^{-1}); arrows indicate predominant summertime flow-patterns, pluses/minuses (+,−) warming/cooling stations, blue/red isotherms cooling/warming areas, red dashed line (extrapolated warming rate), and black isotherms zero-change lines (Lebassi et al., 2009).

et al. 2000; Mintz, 1984; Zhang et al. 1997), irrigation (Christy et al. 2006; Kueppers et al. 2007; Bonfils and Lobell 2007), Greenhouse Gas (Duffy et al. 2007; Walters et al. 2007; Cayan et al. 2008), and/or Urban Heat Islands (LaDochy et al. 2007).

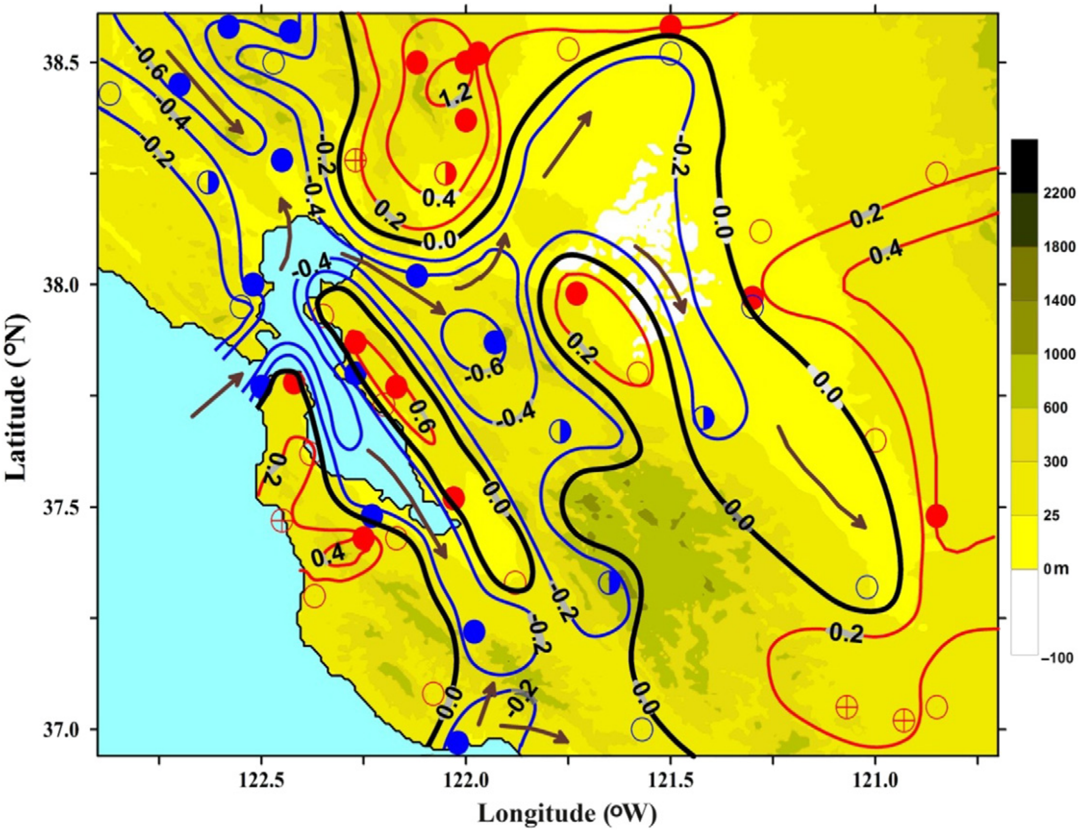
Most recently, Lebassi et al. (2009) evaluated 1970–2005 summer JJA mean monthly maximum air temperatures for two California air basins, SFBA and SoCAB, using data from 253 California COOP weather sites and looking at daily minimum (T_{min}) and maximum (T_{max}) temperatures in order to obtain average monthly values (T_{ave}). They found that when values for all stations were combined, that period showed a general increase of 0.23 °C decade^{-1}. As previously stated by other authors, this warming trend is asymmetric since T_{min} values (0.27 °C decade^{-1}) increased faster than T_{max} values (0.04 °C decade^{-1}). These results are consistent with the previously observed asymmetric global warming (due to increased greenhouse gases). However, the most important aspect of that work is the fact that the T_{max} values in both air basins exhibited a complex pattern with cooling in the low-elevation coastal areas open to marine air penetration and warming at both inland and higher elevation coastal areas (Figures 26 and 27).

In SoCAB subareas, the statistical significance of T_{max} trends show unexpectedly larger trends and higher significance levels for a coastal cooling area (−0.33 °C decade^{-1} and 87%, respectively) than for an inland-warming area (0.21 °C decade^{-1} and 74%, respectively). On the other hand, statistical significance levels in the cooling and warming regions in the SFBA show stronger trends and higher significance values for the inland-warming areas (0.47 °C decade^{-1} and 95%, respectively) than the coastal cooling areas (−0.16 °C decade^{-1} and 72%, respectively), reversed from the SoCAB results because of the more complex SFBA topography (Lebassi et al. 2009). Both inland areas have a combined warming rate of 0.40 °C decade^{-1} and a 93% significance level, while the weaker combined coastal cooling rate (−0.22 °C decade^{-1}) was significant only at the 83% level. The authors hypothesized that this cooling effect was the consequence (and may be a 'reverse reaction') of global warming in inland areas, which resulted in increased sea breeze flow activity. This hypothesis is supported by General Circulation Models T_{ave} output, which showed warming that decreased from 0.13 °C decade^{-1} at inland sites to 0.08 °C decade^{-1} in coastal areas for the same time period and also sea-level pressure increases in the Pacific High and decreases in the inland thermal low. Moreover, pressure gradients showed a trend of 0.04 hPa, 100 km^{-1} decade^{-1}.

However, this coastal cooling effect takes place in the rest of the California coast and is not only reserved for the two air basins. Figure 28 shows the distribution of the maximum monthly T_{max} trends for the summer across the state of California. Similar patterns to the ones seen in the two air basins are shown within the entire state, that is, cooling trends at low-elevation coastal sites and warming trends at both inland and high-elevation sites. More extensive statistical analyses of the distribution of these trends show that the majority of the cooling sites are located at elevations lower than 100 m above sea level as well as distances from the coast less than 70 km, which suggests that 100 m and 70 km are good threshold values to classify a location as a low or a high-elevation site as well as a coastal or an inland site. Also, these values determine the extent of the sea-breeze intrusion and thus the spatial extent of this coastal cooling effect.

3.01.4.2 California Surface Air Temperature Extremes and Heat Waves

Impacts of climate on energy may also be reflected on peak demands, which result from extreme events, such as heat waves. In previous sections, the trends on peak energy demands were discussed for California (Figures 22 and 23). Summer energy peaks may be the result of heat waves. Heat waves may increase in frequency, severity, duration, or areal


Latitude (°N)
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37.5
37.0
Longitude (°W)
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122.0
121.5
121.0
2200
1800
1400
1000
600
300
25
0 m
–100
-0.6
-0.4
-0.2
1.2
0.4
0.2
0.0
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0.6
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Figure 27 Same as Figure 26, but for SFBA (Lebassi et al. 2009).

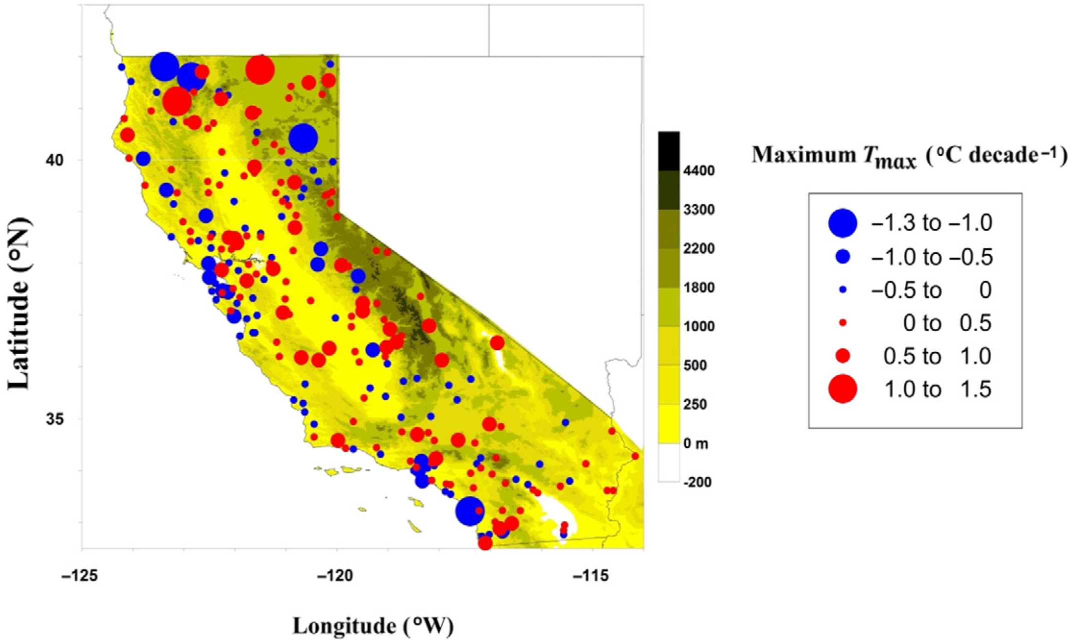
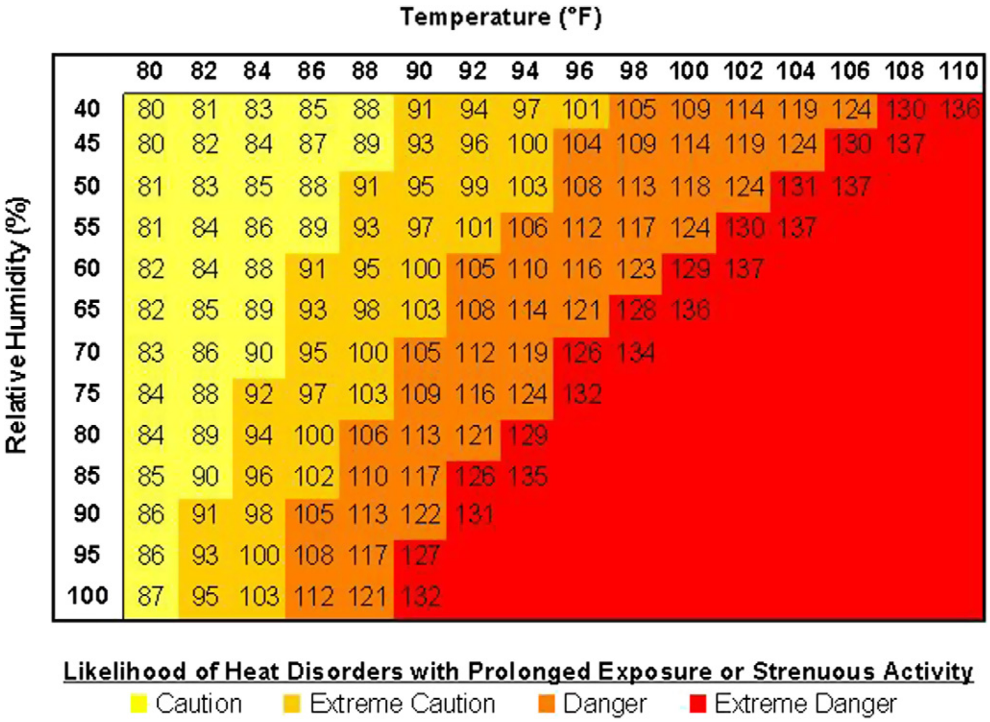

Latitude (°N)
40
35
Longitude (°W)
–125
–120
–115
4400
3300
2200
1800
1000
500
250
0 m
-200
Maximum T_{max} (°C decade^{-1})
–1.3 to –1.0
–1.0 to –0.5
–0.5 to 0
0 to 0.5
0.5 to 1.0
1.0 to 1.5

Figure 28 All California 2-m summertime maximum-temperature trends (°C decade^{-1}) 1970–2010; blue points represent cooling trends while red points represent heating trends. Size of the symbol indicates higher absolute value of the trend.



Temperature (°F)

Relative Humidity (%)	80	82	84	86	88	90	92	94	96	98	100	102	104	106	108	110
40	80	81	83	85	88	91	94	97	101	105	109	114	119	124	130	136
45	80	82	84	87	89	93	96	100	104	109	114	119	124	130	137	
50	81	83	85	88	91	95	99	103	108	113	118	124	131	137		
55	81	84	86	89	93	97	101	106	112	117	124	130	137			
60	82	84	88	91	95	100	105	110	116	123	129	137				
65	82	85	89	93	98	103	108	114	121	128	136					
70	83	86	90	95	100	105	112	119	126	134						
75	84	88	92	97	103	109	116	124	132							
80	84	89	94	100	106	113	121	129								
85	85	90	96	102	110	117	126	135								
90	86	91	98	105	113	122	131									
95	86	93	100	108	117	127										
100	87	95	103	112	121	132										

Likelihood of Heat Disorders with Prolonged Exposure or Strenuous Activity

🟨 Caution 🟨 Extreme Caution 🟧 Danger 🟥 Extreme Danger

Figure 29 Heat index (H_i) (°F) = f(T, RH); from NOAA website, where a T of 95 °F (35 °C) and RH of 50% yields a H_i of 105 °F (Robinson, 2000).

extent due to the effect of global warming. Heat waves may also decrease due to the 'reverse reaction' discussed in the previous section. The U.S. National Weather Service (NWS) declares heat watches and warnings when the heat index is greater than or equal to 105 °F (40.56 °C) during the daytime and greater than or equal to 80 °F (26.66 °C) at nighttime for at least two consecutive days or for a period of at least 48 consecutive hours. Robinson (2000) proposed that extended heat waves exist, if the period is 96 consecutive hours or greater. The heat index (H_i) is a combination of ambient temperature and humidity that approximates the environmental aspect of the thermal state regime of the human body, with NWS thresholds representing a generalized estimate of the onset of physiological stress.

Daily maximum temperatures (T_{max}) for 28 Cooperative network sites in SoCAB from 1970 to 1974 and 2006 to 2010 were analyzed to investigate frequency and intensity of heat waves in California. The NCDC web climate record documented that average summer SoCAB afternoon relative humidity (RH) is about 50–60%. The National Oceanic and Atmospheric Administration (NOAA) gives a heat index value of 105 °F (40.56 °C) for a temperature of 95 °F (35 °C) and RH value of 50%, shown in Figure 29. As we do not have nighttime temperature values, our heat wave and extended heat wave criteria thus only involve daytime T_{max} values greater than or equal to 95 °F (35 °C) for two and four consecutive days, respectively.

As many climate impacts depend on extreme T_{max} values and not just average monthly T_{max} values, Figure 30 shows the SoCAB distribution of the highest T_{max} values anytime during the period from 1970 to 2010. Three subareas are visible with a boundary temperature of 34 °C (and with the following ranges): (a) cool coastal (27–34 °C), (b) cool mountaintops (28–34 °C), and (c) in-between hot area (34–40 °C). Trends in these extreme T_{max} values are shown in Figure 30: (a) decreases up to −0.8°C per decade in the coastal cooling areas, (b) increases up to 0.6°C per decade in the inland and mountain warming areas, and (c) increases up to 0.4 °C per decade in the high-elevation coastal warming areas. Note that these trends are even larger than those in the monthly averaged T_{max} values in Lebassi et al. (2009). Also note the extension of coastal cooling into the mountain pass on the northern SoCAB edge and into the eastern valleys of the basin.

The analysis of spatial distribution of 1970–74 and 2006–10 in days year^{-1} (Figures 31 and 32, respectively), with daily T_{max} greater than or equal to (a) 85 °F (29.44 °C), (b) 90 °F (32.22 °C), and (c) 95 °F (35 °C), resulted in coastal and mountain areas having fewer hot days and inland areas having more hot days. Isopleths increment and boundary value (but not boundary location) change from graph to graph. The difference between 2006–10 and 1970–74 in days year^{-1} (Figure 33), with daily T_{max} greater or equal (a) 85 °F (29.44 °C), (b) 90 °F (32.22 °C), and (c) 95 °F (35 °C), resulted coastal low-elevation areas having large decreases, of up to −32, −24, and −16 days year^{-1}, for 85 (29.44 °C) to 95 °F (35 °C), respectively. Mountain areas have large increases, of up to 28, 20, and 12 days year^{-1}, for 85 (29.44 °C) to 95 °F (35 °C), respectively. Inland low-elevated areas and elevated coastal areas have smaller increases, of up to 18, 8, and 4 days year^{-1}, for 85 (29.44 °C) to 95 °F (35 °C), respectively. Maximum decreases in hot days were not located at the coast, as the coastal effect was always there.

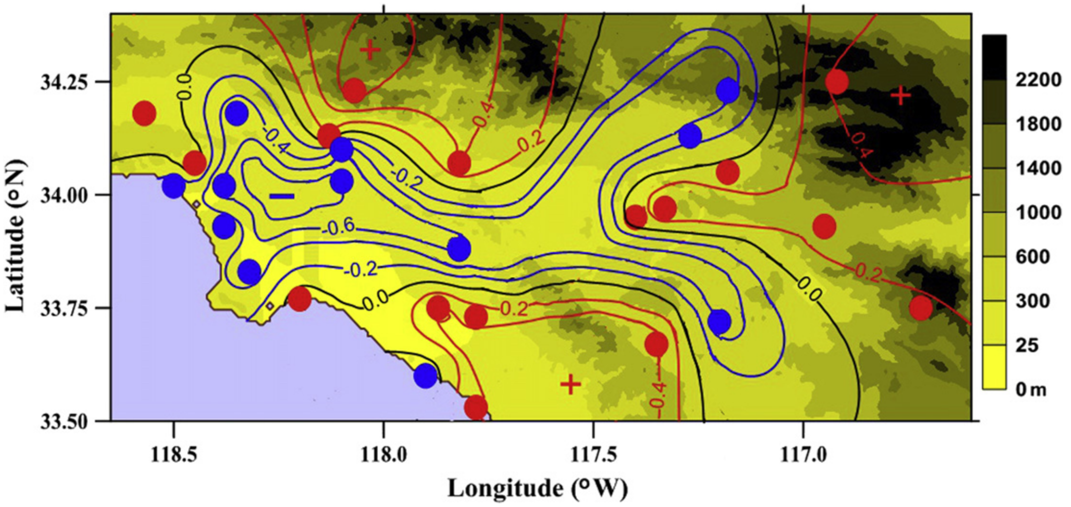


Figure 30 Extreme (highest) T_{max} (°C) value anytime from 1970 to 2010 (upper) and their trends (°C decade^{-1}) over that period (lower).

The analysis of spatial distribution of exactly 2-day heat waves and 4-day heat waves in days year^{-1} (**Figures 34 and 35**), with T_{max} greater than or equal to 95 °F in (a) 1970–74, and (b) 2006–10 resulted in a maximum number of heat waves in inland areas, few in coastal areas, and none in mountain areas. The analysis of changes (**Figures 34 and 35**) (c) 2006–10 values minus 1970–74 values period indicates the following. For coastal low-elevation areas there are large decreases, of up to −11 days 5 years. For mountain areas there is no significant change. For inland low-elevation areas and elevated coastal areas there are smaller increases, of up to 4 days 5 years.

3.01.4.3 Temperature Forecasts in California

The relationship between climate and energy for California was discussed in great detail in previous sections of this chapter. In this section, the surface temperature trends are forecasted for the future by using downscaled outputs from a series of Global Circulation Models (GCMs) under different projected climatic scenarios for the twenty-first century. The focus in this section is centered on the variation of surface.

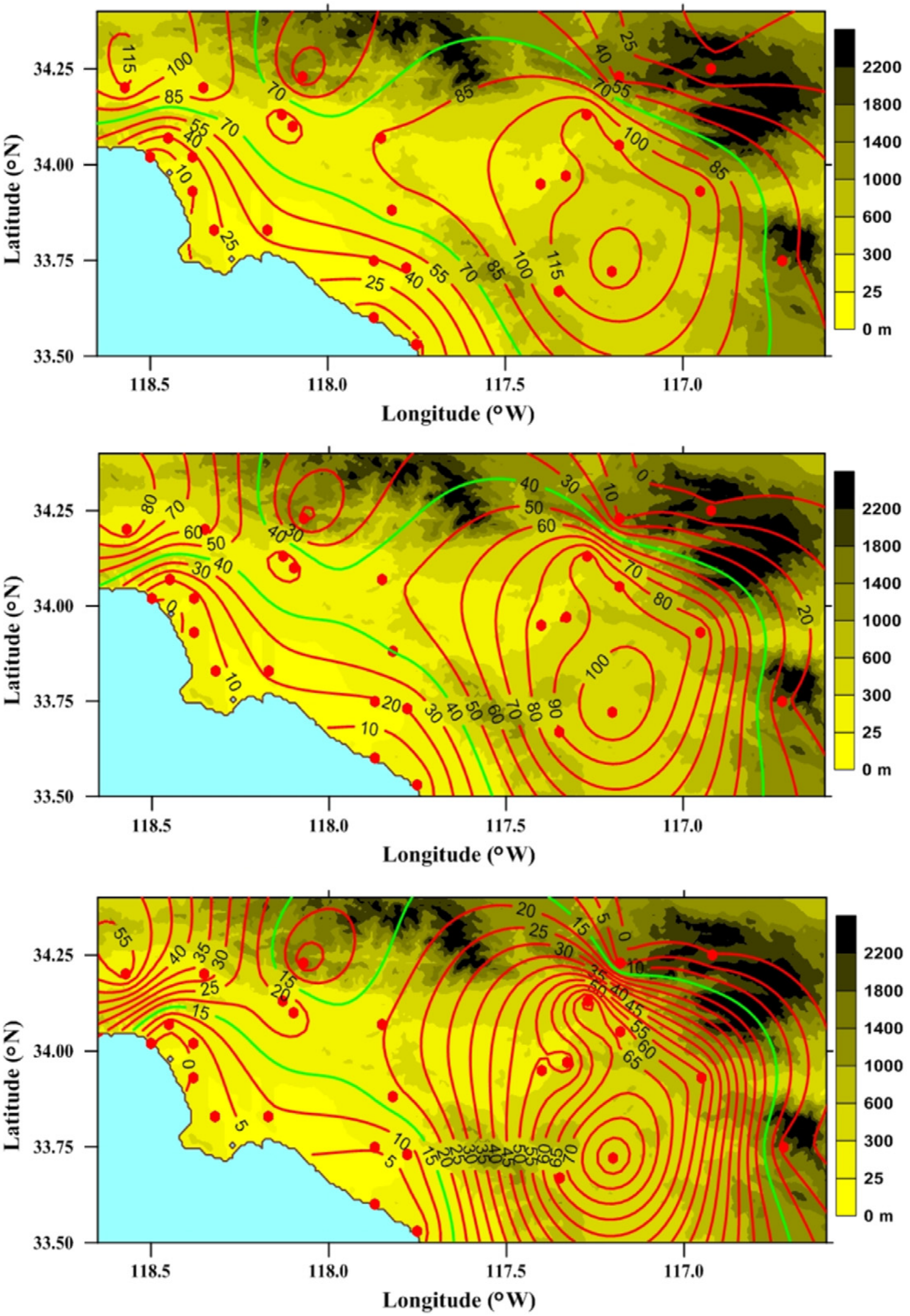
Outputs from monthly average temperature simulations from two scenarios (A2 and B1) for future greenhouse gas emissions forcing global climate are used to estimate electricity demands for the summer in the twenty-first century in California. It should be noted that these scenarios are defined in the Intergovernmental Panel on Climate Change Special Report on Emissions Scenarios (SRES) (IPCC 2000) and each one is simulated by 16 CMIP3 models. CMIP3 stands for the World Climate Research Programme's (WCRP's) Coupled Model Intercomparison Project, Phase 3: Multi-Model Dataset (CMIP2 models). CMIP3 models include BCCR-BCM2.0, CGCM3.1, CNRM-CM3, CSIRO-Mk3.0, GFDL-CM2.0, GFDL-CM2.1, GISS-ER, INM-CM3.0, IPSL-CM4, MIROC3.2, ECHO-G, ECHAM5, MRI-CGCM2.3.2, CCSM3, PCM and UKMO-HadCM3.

The models used in this work were taken from the "Bias Corrected and Downscaled WCRP CMIP3 Climate Projections" archive at http://gdodcp.ucllml.org/downscaled_cmip3_projections. This archive contains 112 projections of monthly temperature and precipitation at 1/8 degree resolution over the contiguous United States, developed using the "Bias-Correction Spatial Disaggregation" (BCSD) downscaling technique (Maurer et al. 2007).

Trends for summer average temperature for three periods (1950–2010, 2011–40, and 2041–70) were obtained by using the median for average JJA temperatures of the 16 models for each of the two scenarios. The SRES A2 (~'higher' emissions path) considers slower technological change and economic growth and higher population growth, while the SRES B1 (~'lower' emissions path) considers rapid change in economic structures toward service and information, with emphasis on clean sustainable technology, as well as reduced material intensity and improved social equity.

The first period (1950–2010) corresponds approximately to the same period presented in the previous section. This period (**Figure 36**) shows similar patterns with lower trends toward the coast (0.10–0.12 °C decade^{-1}) and higher temperature increases for the same period at inland regions (up to 0.3 °C decade^{-1}). It is important to note that these trends are consistent with the observational analyses performed by Lebassi et al. (2009). However, the models are unable to capture the coastal cooling features. This is probably due to the fact that these models were statistically downscaled from the original runs with 2° resolution grids and the coastal cooling phenomena occur at smaller scales (approximately 0.5°).

The second period (2011–40) shows similar spatial patterns than the previous period but the trend values are different in both scenarios, and also, the values increase with respect to the previous period. The A2 scenario (**Figure 37**) presents values that range from 0.19 °C decade^{-1} at the coast to 0.45 °C decade^{-1} further inland while the B1 scenario (**Figure 38**) has similar values to the 1950–2010 period (0.1–0.27 °C decade^{-1}). Finally, the third period (2041–70), as expected, reflects highly increasing trends all over the region for both scenarios, being the A2 scenario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25
0 m

Figure 31 Spatial distribution of 1970–74 days year^{-1} with daily-$T_{\max}$ greater or equal to (a) 85 °F (29.44 °C), (b) 90 °F (32.22 °C), and (c) 95 °F (35 °C).

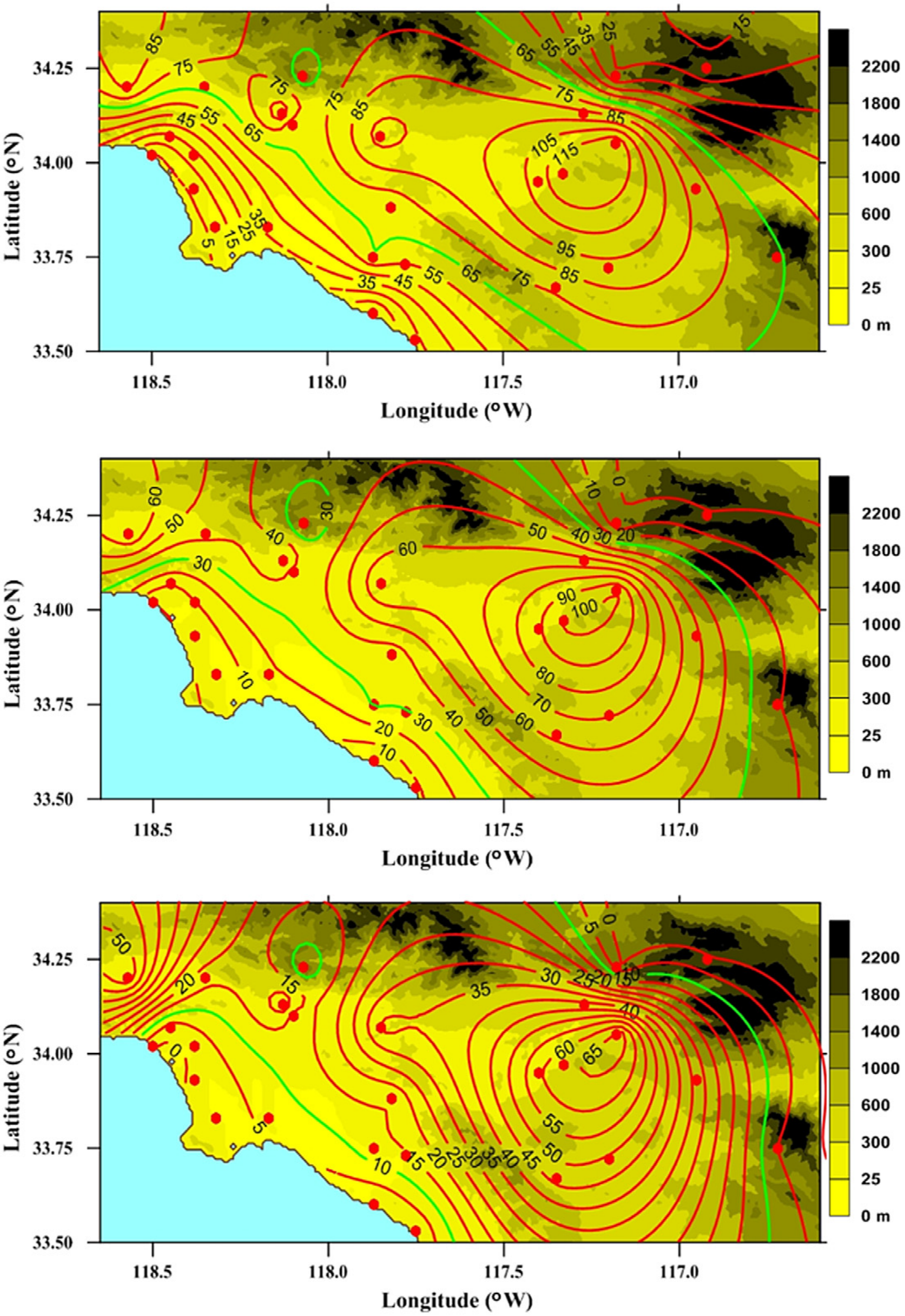
Latitude (°N)
34.25
34.00
33.75
33.50
Longitude (°W)
118.5
118.0
117.5
117.0
2200
1800
1400
1000
600
300
25
0 m

Figure 32 Spatial distribution of 2006–10 days year^{-1}, with daily $T_{\max}$ greater or equal to (a) 85 °F (29.44 °C), (b) 90 °F (32.22 °C), and (c) 95 °F (35 °C).

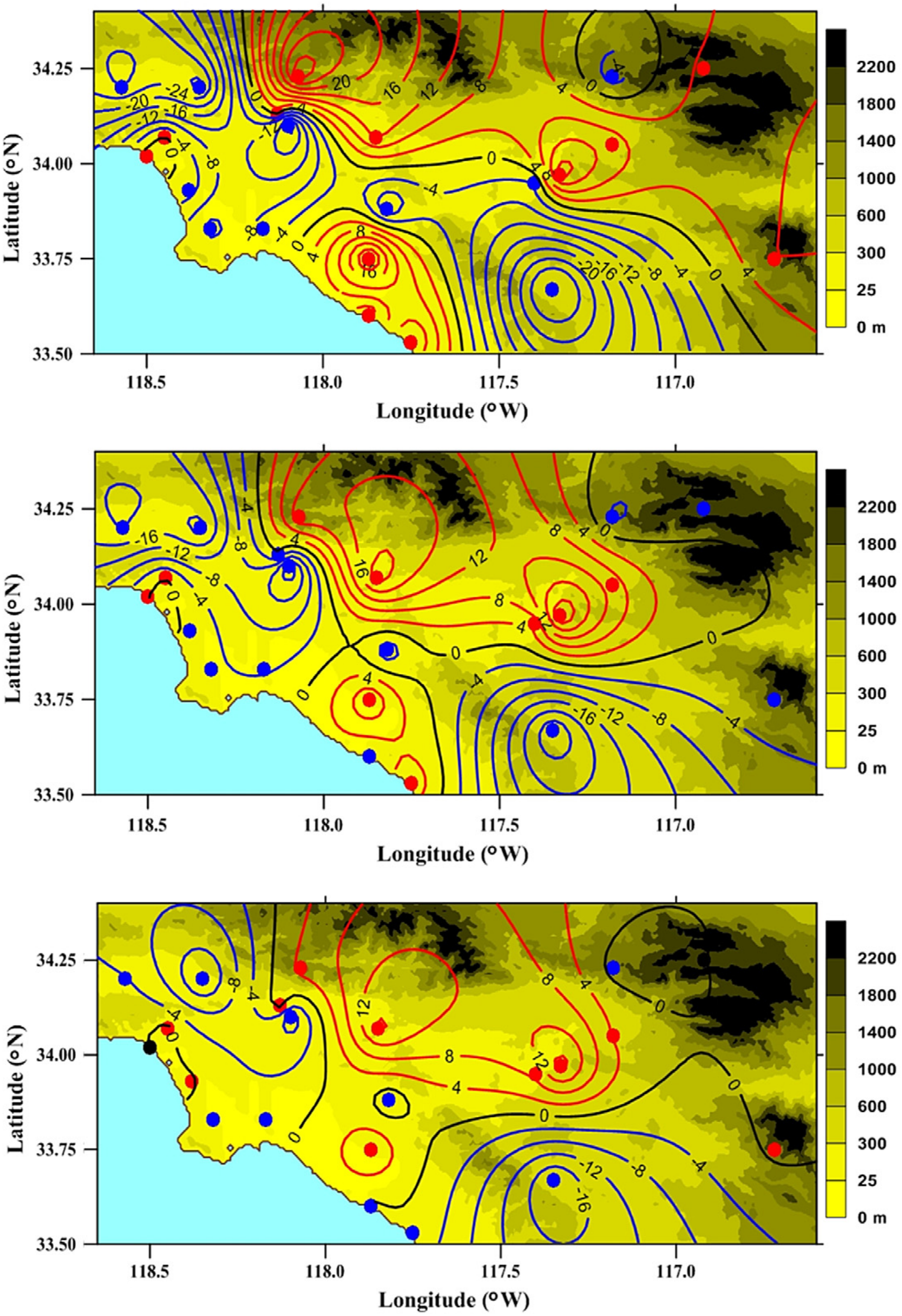
Latitude (°N)
34.25
34.00
33.75
33.50
Longitude (°W)
118.5
118.0
117.5
117.0
2200
1800
1400
1000
600
300
25
0 m
-24
-20
-16
-12
-8
-4
0
4
8
12
16
20

Figure 33 Spatial distribution of difference between 2006–10 and 1970–74, days year^{-1}, with daily T_{max} greater or equal to (a) 85 °F (29.44 °C), (b) 90 °F (32.22 °C), and (c) 95 °F (35 °C).

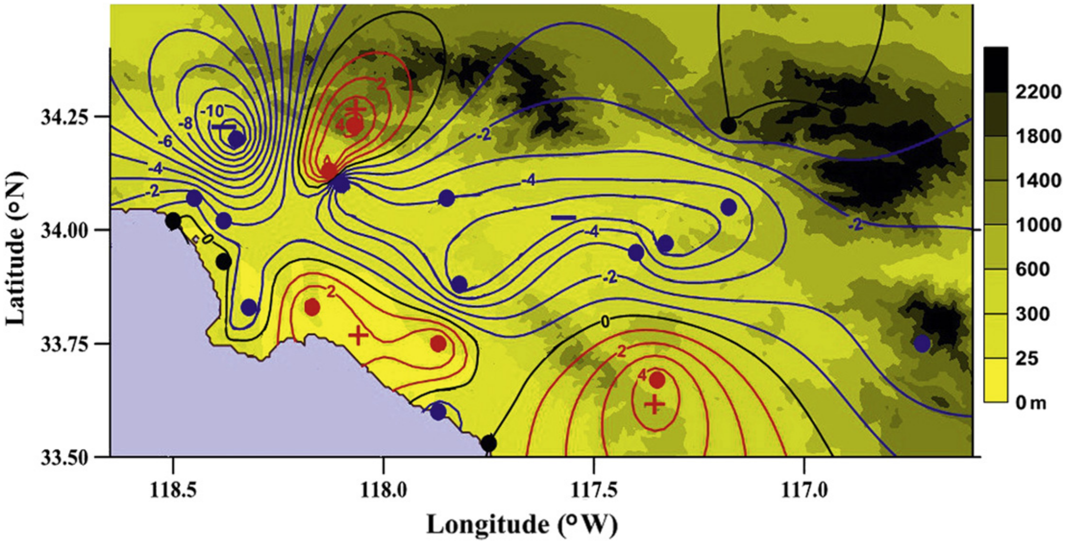

Figure 34 Spatial distribution of exactly 2-day heat-waves (days per 5-years) with $T_{\max}$ greater or equal 95 °F (35 °C) in (a) 1970–74, and (b) 2006–10, and (c) 2006–10 values minus 1970–74 values.

(0.2–0.74 °C decade^{-1}) (Figure 39) overall higher than the B1 scenario (0.16–0.64 °C decade^{-1}) (Figure 40). It is also important to note that the spatial pattern for the A2 scenario changes as the temperature increases with latitude instead of distance from the coast.

3.01.4.4 Climate Trends in the US Northeast Corridor

An accumulation of scientific evidence over the past decade reveals that climate change impacts are already being experienced in the NEC (Hayhoe et al. 2007). Previous sections of this chapter explored the long-term trends of energy demands in California and the NEC. This section details the trends in climate as reflected in changes surface temperatures and precipitation on the NEC for the past 30 years (1980-2010).

Surface temperature and precipitation datasets were used to produce this analysis. Monthly records from NWS COOP stations were used in the analysis. Precipitation and temperature data from 372 stations over the 9 states in the Northeast region were used for a period of time comprising from 1980 to 2010. Mean maximum and minimum surface temperature as well as precipitation profiles were generated by examining inland and coastal areas. The criteria to select the stations were based on the diversity of the regions to capture axisymmetric warming trends (Karl et al. 1988). The three variables utilized to generate the dataset were maximum mean surface temperature ($T_{\max}$), minimum mean surface temperature ($T_{\min}$), and mean precipitation. The data consisted of daily $T_{\min}$ and $T_{\max}$ temperatures. Daily average temperatures were used to produce average monthly $T_{\max}$ and $T_{\min}$ temperatures. Months with more than 5 days of missing data and/or sites with less than 15 years of data were not used in the analysis. This effort produced a comprehensive climatology dataset for the Northeast region.

Two phenomena were observed in the NEC region that clearly show warming and cooling regions. The NCDC COOP stations $T_{\max}$ data show that the whole NEC coast is warming in the period of time that comprised the last 30 years (Figure 41). A total $T_{\max}$ and $T_{\min}$ variability of 0.011 and 0.061 °C decade^{-1}, respectively, were observed during this period of time. Also, in Figure 41 it can be observed that the $T_{\min}$ trend warmed faster than the $T_{\max}$ trend. Some studies suggest that a slow variation in $T_{\max}$ could be due to irrigation and other agricultural land-use practices (Chase et al. 2000; Betts 2001), but an acceleration in a warming $T_{\min}$ trend may also be the result of deforestation (Pielke et al. 2002; Defries et al. 2002). An examination of the spatial trends in the NEC region (Figures 42 and 43) shows that while the $T_{\max}$ warming trend is slower, most of the stations in the NEC had an increasing trend. Most notably is the 2 °C decade^{-1} increase in the Portland, Maine COOP station. Certain inland areas are showing the opposite trend. For example, these regions, such as the rural area of Chemung, New York, show cooling during the summer time. However, inland areas that are densely populated, such as the Pittsburgh metro region, show warming trends that can be attributed to UHI effects. Most major metro regions are located in coastal regions and show warming patterns for both $T_{\max}$ and $T_{\min}$, which could be attributed to a combined effect of global warming and UHI. The summer maximum for inland areas reflects an increase of 0.2 °C decade^{-1} (see Figure 42). In contrast, the summer maximum for coastal areas shows warming sites increasing at a rate of 0.4 °C decade^{-1} (as shown in Figure 42). Winter climate reflects all warming $T_{\min}$ sites across the region with a maximum of 2 °C decade^{-1} (Figure 43). In summary, observations show that the NEC coast is warming during the summer and during the winter at a faster rate. These results contrast with the California case, as previously discussed, during the summer but entirely agree for the winter.

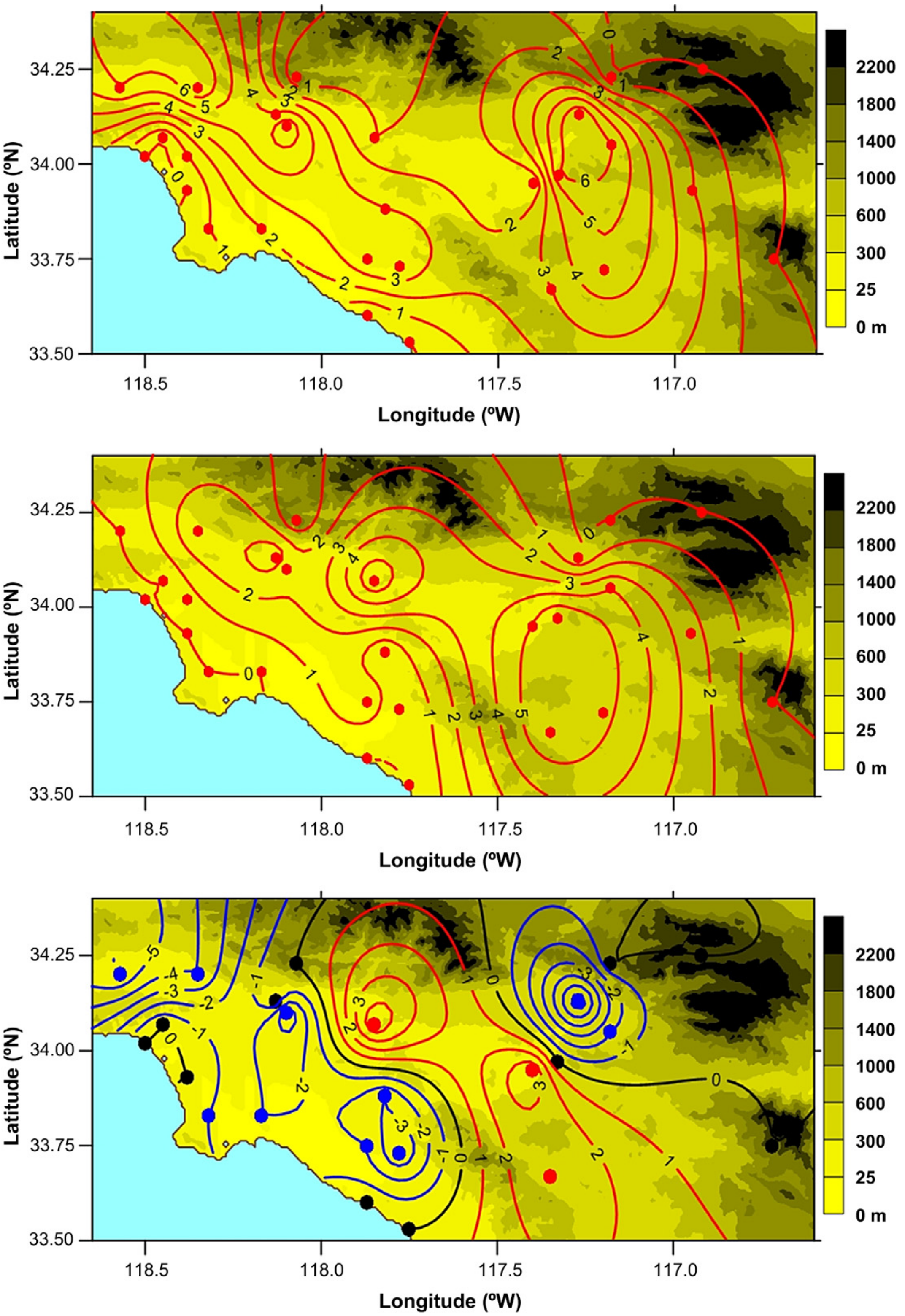
Latitude (ºN)
34.25
34.00
33.75
33.50
118.5
118.0
117.5
117.0
Longitude (ºW)
2200
1800
1400
1000
600
300
25
0 m

Figure 35 Spatial distribution of exactly 4-day heat-waves (days per 5-years) with T_{max} greater or equal 95 °F (35 °C) in (a) 1970–74, and (b) 2006–10, and (c) 2006–10 values minus 1970–74 values.

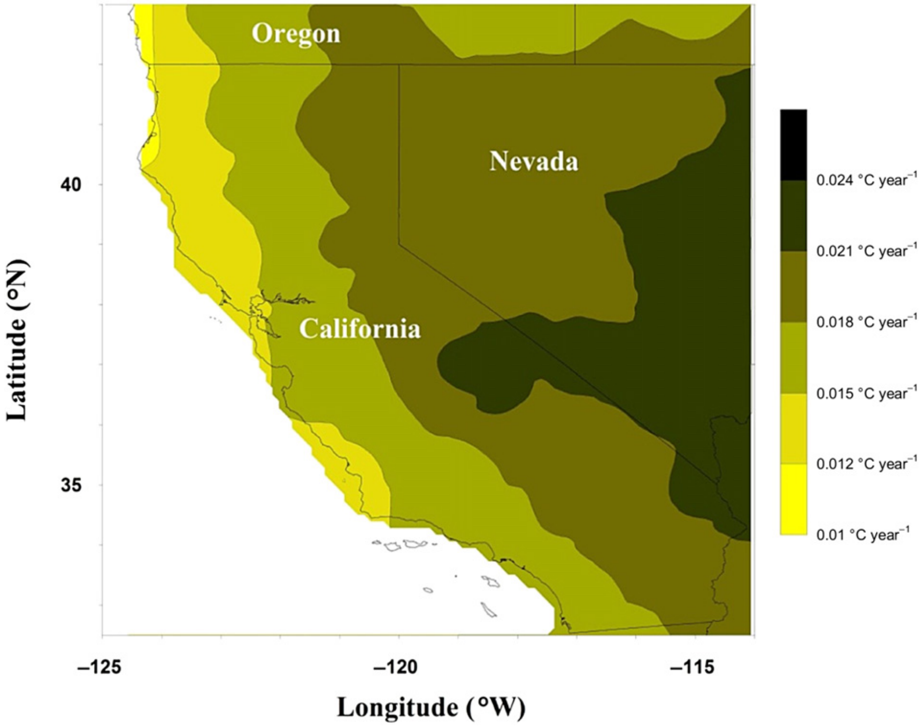
Oregon
Nevada
California
Latitude (°N)
40
35
–125
–120
–115
Longitude (°W)
0.024 °C year^{-1}
0.021 °C year^{-1}
0.018 °C year^{-1}
0.015 °C year^{-1}
0.012 °C year^{-1}
0.01 °C year^{-1}

Figure 36 Summertime 1950–2010 monthly averaged temperature trend (°C year^{-1}).

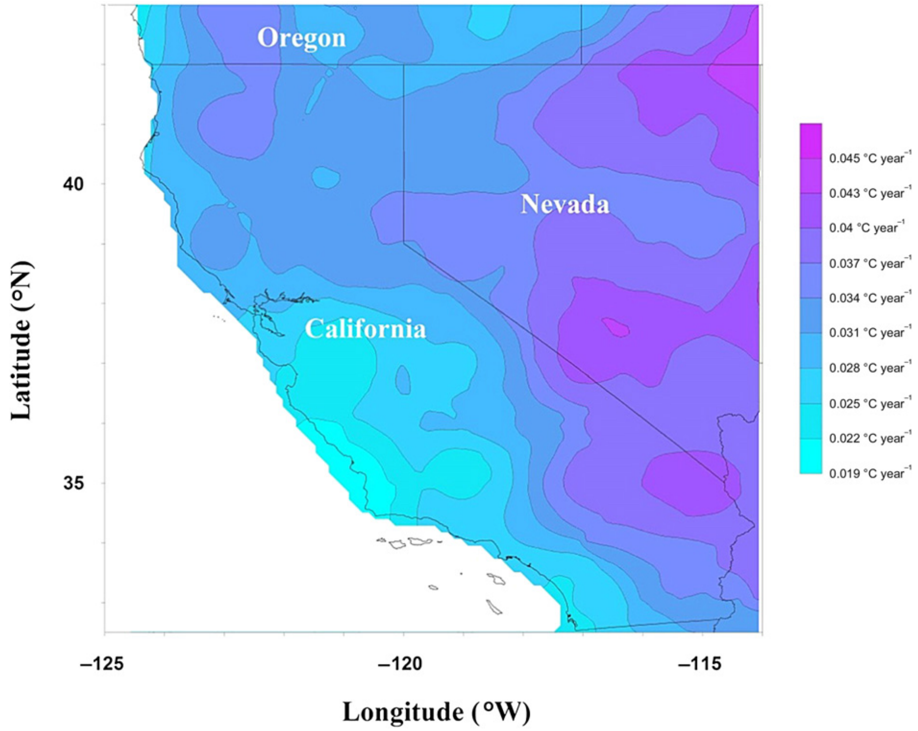
Oregon
Nevada
California
Latitude (°N)
40
35
–125
–120
–115
Longitude (°W)
0.045 °C year^{-1}
0.043 °C year^{-1}
0.04 °C year^{-1}
0.037 °C year^{-1}
0.034 °C year^{-1}
0.031 °C year^{-1}
0.028 °C year^{-1}
0.025 °C year^{-1}
0.022 °C year^{-1}
0.019 °C year^{-1}

Figure 37 Downscaled CMIP3 summertime 2011–40 monthly averaged temperature trend. Scenario A2 (°C year^{-1}).

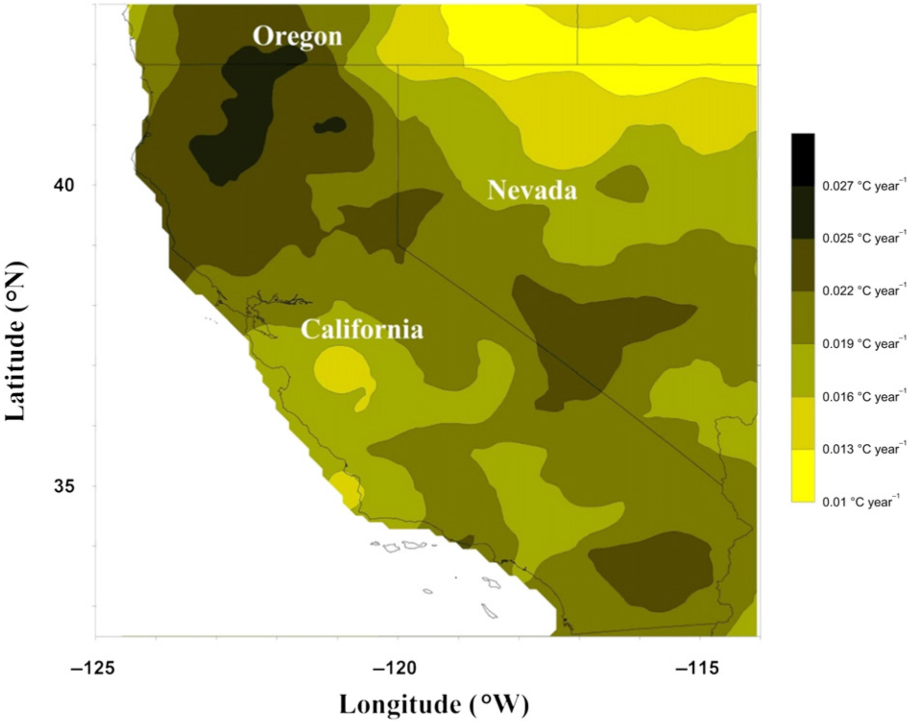
Oregon
Nevada
California
Latitude (°N)
40
35
Longitude (°W)
–125
–120
–115
0.027 °C year⁻¹
0.025 °C year⁻¹
0.022 °C year⁻¹
0.019 °C year⁻¹
0.016 °C year⁻¹
0.013 °C year⁻¹
0.01 °C year⁻¹

Figure 38 Downscaled CMIP3 summertime 2011–40 monthly averaged temperature trend. Scenario B1 (°C year^{-1}).

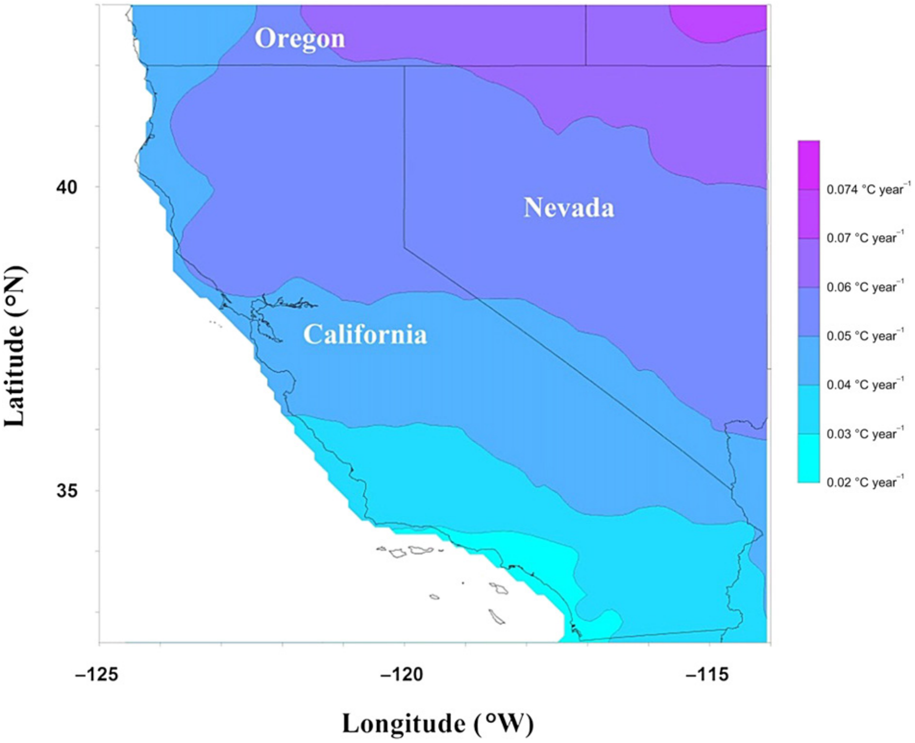
Oregon
Nevada
California
Latitude (°N)
40
35
Longitude (°W)
–125
–120
–115
0.074 °C year⁻¹
0.07 °C year⁻¹
0.06 °C year⁻¹
0.05 °C year⁻¹
0.04 °C year⁻¹
0.03 °C year⁻¹
0.02 °C year⁻¹

Figure 39 Downscaled CMIP3 summertime 2041–70 monthly averaged temperature trend. Scenario A2 (°C year^{-1}).

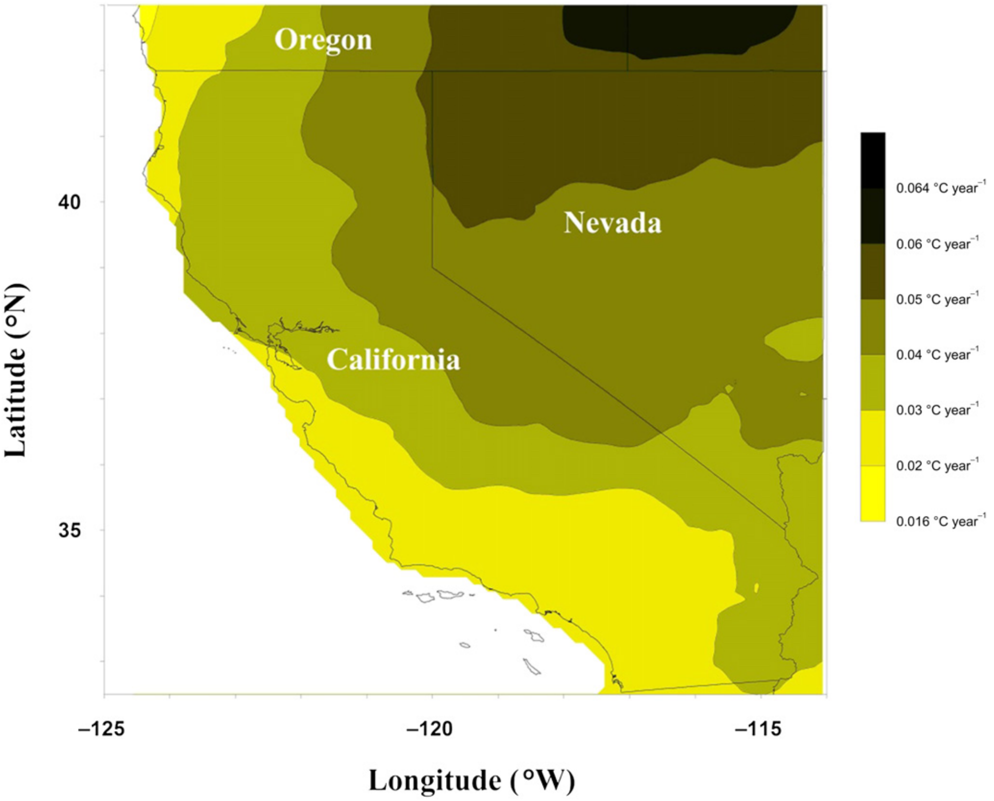
Oregon
Nevada
California
40
35
Latitude (°N)
–125
–120
–115
Longitude (°W)
0.064 °C year^{-1}
0.06 °C year^{-1}
0.05 °C year^{-1}
0.04 °C year^{-1}
0.03 °C year^{-1}
0.02 °C year^{-1}
0.016 °C year^{-1}

Figure 40 Downscaled CMIP3 summertime 2041–70 monthly averaged temperature trend. Scenario B1 (°C year^{-1}).

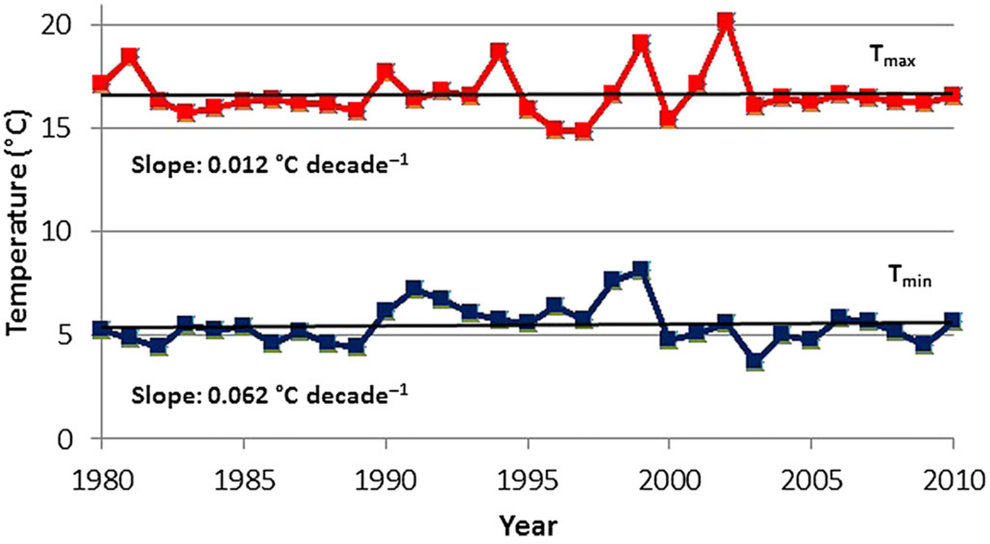

Figure 41 Total variation of T_{max} and T_{min} (1980–2010) for the U.S. North East Region.

The climate trend analysis also shows a uniform increase in precipitation within the region. Figure 44 shows that the entire NEC region has an increasing precipitation trend with inland sites presenting an increase of mean precipitation in the order of 0.2 mm decade^{-1}, while coastal sites in the entire NEC had an average positive change of 0.21 mm decade^{-1}. While the focus of this chapter is on end-user demands, precipitation findings suggest that water supplies may not risk energy production by hydro-sources for the NEC.

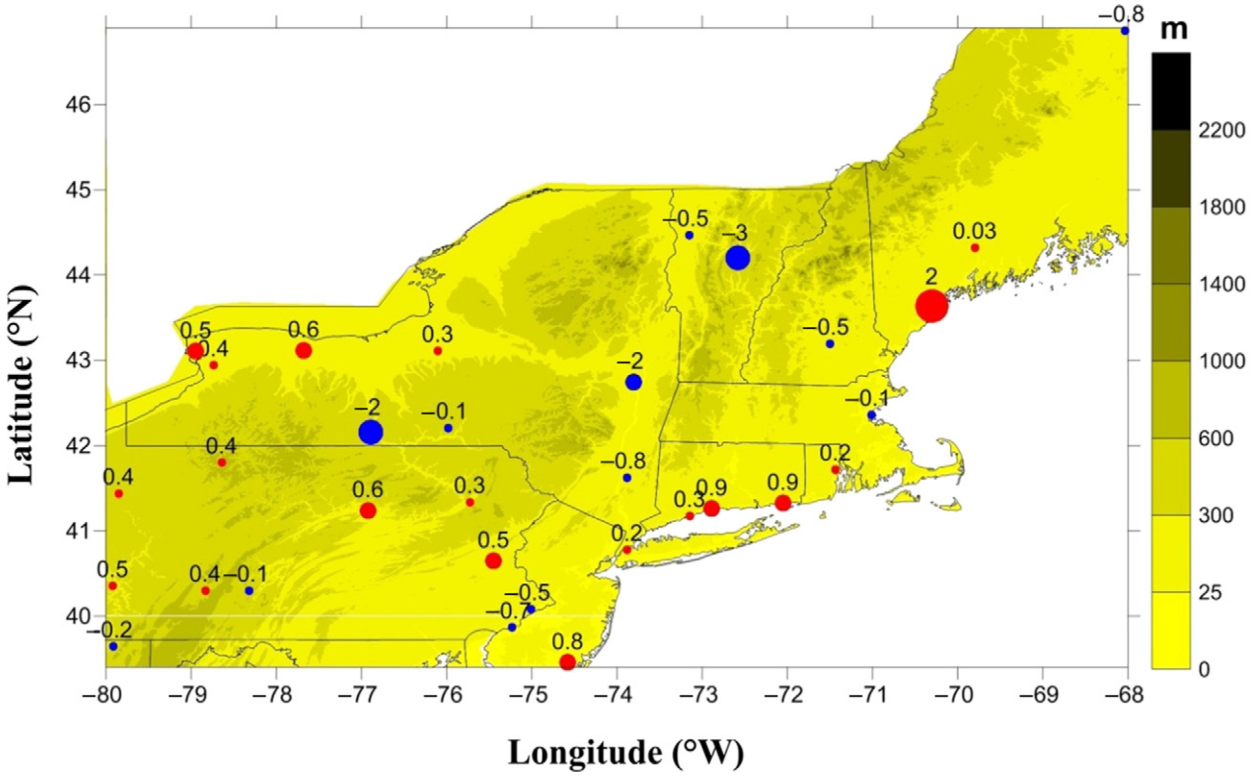
m
2200
1800
1400
1000
600
300
25
0
Latitude (°N)
46
45
44
43
42
41
40
Longitude (°W)
−80
−79
−78
−77
−76
−75
−74
−73
−72
−71
−70
−69
−68
−0.8
−0.5
−3
0.03
2
0.5
0.4
0.6
0.3
−0.5
−2
−2
−0.1
−0.1
0.4
0.2
0.4
0.6
0.3
−0.8
0.3
0.9
0.9
0.5
0.2
0.5
0.4
−0.1
−0.5
−0.7
−0.2
0.8

Figure 42 Annual $T_{\max}$ variability ($^{\circ}$C decade^{-1}) for selected 36 COOP stations. Red dots represent increasing trend and blue dots represent decreasing trend.

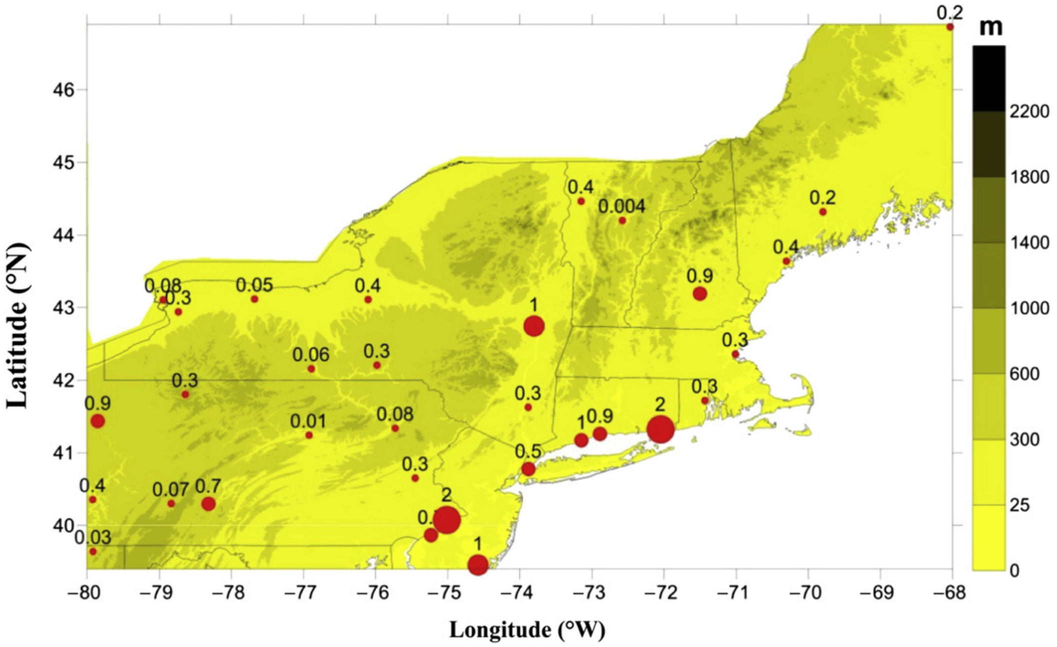
0.2
m
2200
1800
1400
1000
600
300
25
0
Latitude (°N)
46
45
44
43
42
41
40
Longitude (°W)
−80
−79
−78
−77
−76
−75
−74
−73
−72
−71
−70
−69
−68
0.4
0.004
0.2
0.4
0.9
0.08
0.3
0.05
0.4
1
0.3
0.06
0.3
0.3
0.3
0.3
0.9
0.01
0.08
0.3
1
0.9
2
0.3
0.5
0.4
0.07
0.7
2
0.
0.03
1

Figure 43 Annual $T_{\min}$ variability ($^{\circ}$C decade^{-1}) for selected 36 COOP stations. Red dots represent increasing trend and blue dots represent decreasing trend.

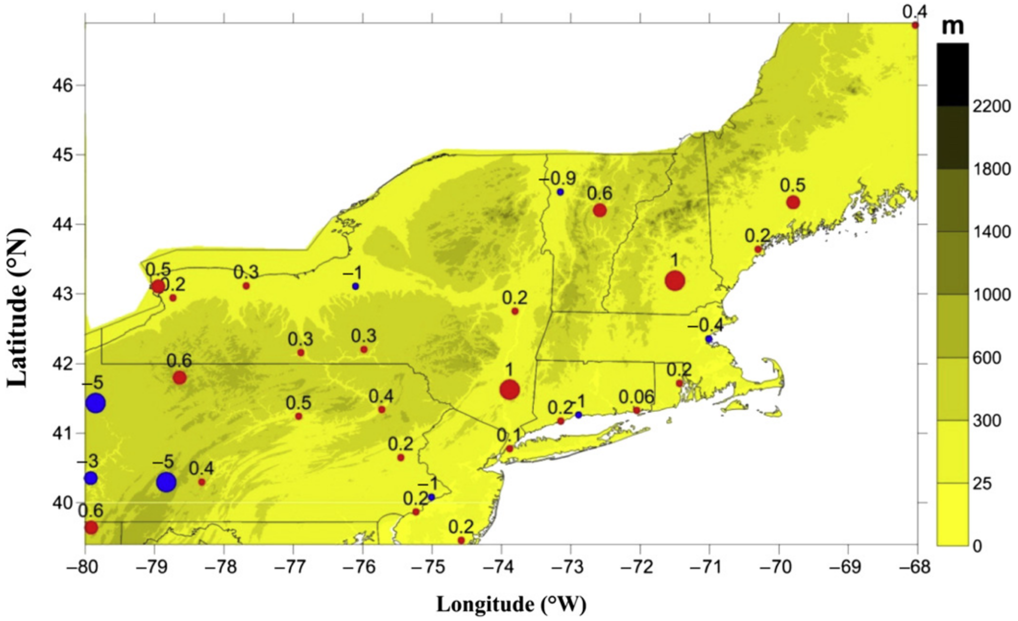

Figure 44 Annual precipitation variability (mm decade^{-1}) for selected 36 COOP stations. Red dots represent increasing trend and blue dots represent decreasing trend.

3.01.5 Summary

This chapter reviewed the relationship between energy and climate trends within the context of populated coastal regions. Energy activity is sensitive to climate in several ways: demand from end users is directly influenced by long climate variability for space heating and cooling of buildings and homes, extreme climate events drive the peak demand grid exposing the vulnerability of the energy production infrastructure, and changes in water supply may impact energy production from hydro-plants. A warming climate in Northern latitudes may, therefore, drive increasing demands in summer time and reduce demands in winter seasons. This chapter looked at the question from the end-user perspective by analyzing climate trends in two distinct coastal regions in the United States; Coastal California and the Northeast Corridor, both similar in population but different in climate. In response to climate patterns, a correlation was found between surface temperature trends and energy demands for the residential sector and little sensitivity in the commercial and industrial sectors. The case of coastal California suggests a decrease in summer peak energy demands consistent with cooling temperature trends, which contrasts with climates warming around the world. This suggests that regions should be carefully looked at to account for local factors such as topography. In general, it can be inferred that Northern latitude energy infrastructures may be less vulnerable to climate trends than anticipated.

Methods used in this chapter may be employed to analyze the nexus between energy and climate in other locations of the world. Future works should also look at the nexus between climate and renewable energy resources such as wind, solar, and hydro power.

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- U.S. National Oceanic and Atmospheric Administration, Office of Education Educational Partnership Program award NA11SEC4810004.
- U.S. National Science Foundation under Grant Nos. AGS-1062934 and 0933414.
- U.S. Department of Education under Grant No. P031M105066.

The statements contained within this chapter are not the opinions of the funding agencies or the U government, but reflect the author's opinions.

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3.02 Energy Resources and Policy: Vulnerability of Energy Resources and Resource Availability – Fossil Fuels (Oil, Coal, Natural Gas, Oil Shale)

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3.02.1 Introduction

3.02.1.1 Growing Global Demand for Energy

Buckminster Fuller is quoted as saying, 'Real wealth is ideas plus energy.' Despite the fact that his statement was not intended to describe the relationship between economic growth and energy use, the quote still succinctly describes the importance of energy in our economy. The global population is growing both in number and in its per capita use of energy as increasing fractions of the world's population come out of poverty. Energy growth is thus growing more quickly than the population. Over 80% of today's energy comes from fossil

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fuels, which are the major anthropogenic source of carbon dioxide (CO_2). CO_2 is one of the first order human climate forcing agents and is of concern because it is the largest human-emitted radiative forcer and has a long (decades to century) atmospheric lifetime (National Research Council 2005, 2010a). The challenge faced by the world is to maintain economic growth, driven by energy, while at the same time reducing carbon emissions. In this chapter, the term 'carbon' refers primarily to CO_2 and methane (CH_4). 'Carbon' is sometimes used as shorthand notation to include radiative forcing agents more generally, including aerosols, which (depending upon composition and location) can result in either increases or decreases in radiative forcing.

The term 'energy' is used here as shorthand for the complex technological systems that extract, refine, transport, and apply the world's energy resources to meet our fundamental demands for food, clean water, transport, space conditioning, and other end uses. The development of such complex technological systems has been likened to the evolution of ecosystems (Arthur 2009). As with biological ecosystems, technological systems evolve to succeed within a range of experienced external conditions. The most successful systems, whether biological or technological, are able to adapt as the range of external conditions change. However, the success of these systems becomes vulnerable when conditions change more rapidly than the ability of the system to respond. Vulnerability is therefore most strongly related to the amplitude and rate of change beyond the historical range of conditions within which a system evolved.

Environmental, industrial, and societal systems – including systems that produce, deliver, and convert energy – that have evolved within historical climate patterns would be impacted in the event of significant decadal-scale changes in temperature, precipitation, and other weather event characteristics. The term 'climate' is used in this chapter as the average temperature and precipitation over a multidecadal period, and includes measures of the type, frequency, and intensity of weather events, and a change in climate likewise refers to a change in the averages of these parameters over a multidecadal period (The 30-year period from 1970 to 2000 is often used as the statistical basis for comparison). There is a potential for these changes to become more pronounced in future years, particularly toward the end of the twenty-first century (Meehl et al. 2007; National Research Council 2010b). Because climate is a long-term phenomenon, and because historical experience indicates that significant changes to the energy system take decades to occur (Kramer and Haigh 2009; Smil 2010), it is appropriate to think about the vulnerabilities of fossil fuel energy resources to climate over a period of several decades. A time frame of about 40 years seems to be appropriate, for several reasons.

The combustion turbine, natural gas-combined cycle power plants, and natural gas liquefaction were in their early stages of development 40 years ago (approximately 1970), and have since helped to drive the global fraction of natural gas consumption from 18 to 24% (see Figure 1), while petroleum consumption dropped from 45 to 35% (although it is still the largest primary energy source). Coal consumption has remained about constant as a fraction of total energy (31% of world primary energy in 1970 and 29% in 2009) (BP 2010).

The year 1970 also marks a point at which consideration of the environment began to play a much greater role in how energy is produced and used, with the founding of the US Environmental Protection Agency as a major indicator of these growing environmental concerns. In the United States, the Clean Air Act was passed in 1970, marking a major advance in the control of air pollutant emissions, largely from energy production systems.

The world's economy had grown by a factor of about 20 since 1970 (World Bank 2011), while world population has almost doubled, from 3.7 billion people in 1970 to 7 billion today (United Nations 2011). Energy consumption has increased slightly faster than population, from 56.5 to 69.2 kJ per person (BP 2010), and CO_2 emissions per person have increased by about 10% over the past 40 years (Boden et al. 2011). Even so, energy use per dollar of GDP and CO_2 emissions per dollar have both dropped by roughly a factor of 10 over the same period.

It is clear that there have been major technical, social, and economic changes over the past 40 years, and these have substantially influenced and have been influenced by the world's energy system (Wilbanks et al. 2008). The importance of energy to economic growth and social well-being is well documented. The question is how global environmental effects, including climate, will influence and be influenced by energy production and use over the *next* 40 years.

A 2009 study, based on a reduced complexity coupled carbon cycle–climate model, estimated that no more than 1000 Gt of CO_2 can be emitted between 2000 and 2050 to have a reasonable probability (more than 25%) of maintaining average global surface air temperature rise to less than 2 °C (Meinshausen et al. 2009). This conclusion is based upon the sensitivity of temperature to atmospheric greenhouse gas (GHG) concentrations as reported in the 2007 Assessment Report from the Intergovernmental Panel on Climate Change (IPCC) (Solomon et al. 2007). To meet this IPCC target, it is likely that per capita CO_2 emissions would need to be roughly 10% of what they are today.

Meeting such levels of CO_2 reductions is a daunting task given the current connections between population growth, economic development, energy use, and CO_2 emissions. A straightforward relationship between these factors is described by the Kaya identity (Yamaji et al. 1991),

$$\mathrm{CO_2} = \text{Population} \times \left(\frac{\text{GDP}}{\text{person}}\right) \times \left(\frac{\text{energy consumption}}{\text{GDP}}\right) \times \left(\frac{\mathrm{CO_2}}{\text{energy consumption}}\right)$$

where GDP is the gross domestic product. From this broad perspective, CO_2 emissions can be reduced by reducing population, per capita GDP, energy per dollar of GDP, or CO_2 per unit energy consumption. From a technological perspective, energy efficiency (energy per dollar of GDP) and low carbon energy (CO_2 per unit energy consumption) are the most common targets for reducing CO_2 emissions. Economic efficiency efforts have resulted in enormous improvements in energy consumption per dollar of GDP and in emissions of CO_2 per dollar of GDP – the product of the last two terms in the Kaya identity. However, the rate of technological

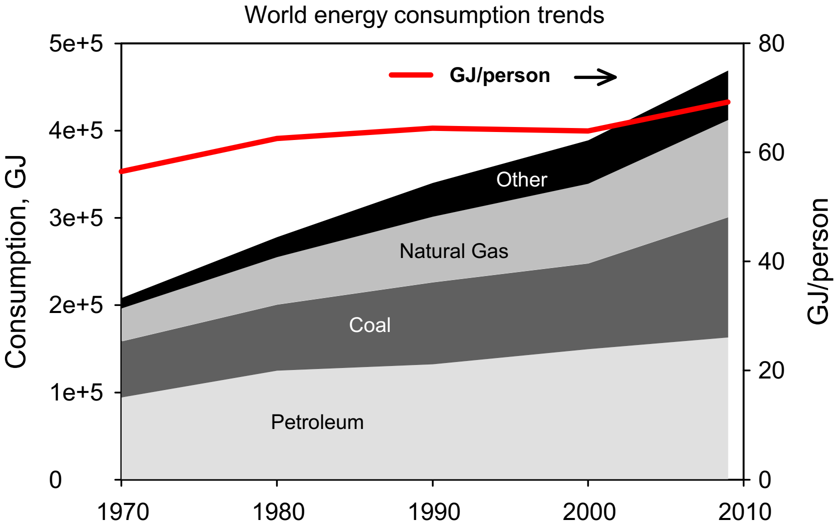

Figure 1 Trends in world energy consumption from 1970 to 2009. Total consumption in GJ is shown by the area plot (scale to the left) and per capita consumption in GJ/person is shown by the red line (scale to the right) (BP 2010).

improvement has not been rapid enough to achieve similar reductions in CO_2 per person (the product of the last three terms above), leading to increases in total global CO_2 emissions.

Even as efficiency acts to drive down energy consumption per economic output, demand for energy continues to rise. Yet, despite rising consumption and concerns that fossil fuel resources are diminishing, proved petroleum reserves have steadily grown over the past 40 years. With the rapidly increasing use of hydraulic fracturing and horizontal drilling, world natural gas proved reserves have also increased by more than a factor of two since 1980 (BP 2010).

With UN population projections estimating nearly 10 billion people by 2050, the demand for the transportation, cooking, heating, cooling, manufacturing, and other services provided by energy will likely remain strong. However, the ability of fossil energy to meet these demands will be impacted by a number of factors, including the extent to which climate-related environmental impacts become more pronounced and if GHG mitigation strategies are adopted.

Fossil fuels are expected to continue to play a major role in the global energy system for the foreseeable future, even if major GHG reduction policies were to be adopted worldwide. The recent World Energy Outlook published by the International Energy Agency (IEA) noted that if current international GHG policy commitments (e.g., those announced at recent climate meetings in Copenhagen and Durban) were to be implemented in full, global energy demand would still increase by 33% from 2010 to 2035. In this scenario, fossil fuels will still make up 75% of primary energy consumption in 2035, representing an increase in total worldwide fossil fuel consumption of about 25%. IEA estimates that if major commitments were to be made to limit atmospheric GHG emissions, overall fossil fuel consumption would fall, but natural gas consumption would still increase over the same time period (IEA 2011). It remains crucial, therefore, to understand the potential vulnerabilities of fossil fuel resources in a future affected by impacts of climate on the environment and the implementation of GHG mitigation policies.

3.02.1.2 Environmental and Social Variables That Influence the Use of Fossil Fuels

The possible adoption of policies to limit carbon emissions and the potential cost of such policies are not the only variables that influence the use or vulnerabilities of fossil fuels. Growing global populations demand more energy. Rising consumption and expectations in emerging economies (particularly China, India, Brazil, and Russia) are driving major increases in demand for energy-intensive products and services, particularly freight and personal transport (IEA 2011). Greater affluence also enables populations to consume more energy-intensive foods, such as beef (McAlpine et al. 2009). As populations grow more affluent, they also place greater value on environmental quality (Franzen 2003). Together, these factors act to drive up demand for fossil energy (given the nearly exclusive use of fossil fuels in the transportation and agricultural sectors) but (at least in the longer term) also place greater environmentally oriented constraints on how fossil fuels are produced and used.

3.02.1.3 Increasing Complexities and Costs of Resource Exploitation

As the demand for fossil fuels has grown, resource production and transport has expanded into increasingly challenging environments (e.g., deep sea and Arctic) and has required development and application of more advanced and more expensive technologies to meet that demand, particularly for petroleum. Financial, management, and regulatory structures supporting fossil fuel exploitation have also grown more complex as investors seek to maximize returns on investments and governments seek to maintain health and environmental protection goals. The growing complexity of the technologies and human systems needed to develop and exploit fossil fuel resources means that the investments, both in terms of finances and energy, needed to produce the next increment of fossil fuel energy continue to grow. As fossil fuel markets become increasingly global, the increasingly complex and expensive measures needed to meet demand and make up for reduced output from easily accessed resources means that it is likely that we have reached 'the end of cheap oil' (IEA 2011).

3.02.1.4 Climate: New Problems, New Responses

In addition to the above global-scale changes and pressures on fossil fuel resources, a change in climate would create further challenges. As resource production moves into environments that are increasingly difficult in which to operate, changes in environmental conditions can exacerbate the financial and technical challenges of resource extraction. Although there is a tremendous amount of experience with fossil fuels in a wide range of environments, decadal-scale changes in weather patterns could alter those environments in fundamental ways, resulting in operating conditions that are outside the ranges for which systems were designed. These problems include permafrost thawing, greater variability in weather (including more extreme conditions), and significant changes to precipitation patterns that could lead to drought in some areas and more severe and extensive flooding in others. These issues will require new technical responses to maintain the production and use of fossil fuel energy, independent of the potential application of carbon emissions constraints. In this particular instance, the term 'technical' covers more than just engineered systems, it also includes the financial, management, and regulatory systems necessary to enable the engineered systems to operate effectively.

3.02.1.5 Scope of Discussion

The focus of this chapter is on the vulnerability of fossil fuel resource extraction, delivery, and use to climate, in the context of the challenges posed by other global-scale changes. In general, fossil fuel resources are not affected by climate but the extraction, transport, and use of the resources are. One major use of fossil fuels, the generation of electricity from thermoelectric generating systems, is also vulnerable to climate, and so represents an additional source of vulnerability to the use of fossil fuels. Vulnerabilities of fossil fuels to GHG mitigation approaches will be discussed, with the focus on the extent to which those approaches have an impact on resources. The chapter will also discuss the different ways in which fossil fuels used in the transportation sector are vulnerable to climate, indirectly through vulnerabilities associated with an increased use of biofuels and electrification.

A common strategy among proposed GHG mitigation approaches is a focus on massive reductions in fossil fuel GHG emissions. If such changes in the global energy system were to occur, they would have similarly massive impacts on the form of the world economy. This chapter does not consider the vulnerabilities to fossil fuel use associated with changes to economies because of GHG mitigation strategies. However, it does recognize that the application of GHG emission reduction technologies would impact the use of fossil fuels, and these impacts are discussed at the scale of a single power generating plant. However, it is well beyond the scope of this discussion to address potential economy-wide impacts and the ensuing implications for fossil fuel use.

3.02.2 Vulnerability to Temperature Change

Fossil fuel production and use technologies have been designed to work within specific temperature ranges that account for variability and extremes of heat and cold. These ranges will, of course, vary with location and are impacted by latitude, altitude, surroundings, proximity to vegetation and water, and other factors. Most systems are able to operate even during short periods in which temperatures are outside the ranges of recent multidecadal measurements. However, energy production and use systems can be vulnerable to significant changes in temperature ranges or the duration and magnitude of extreme temperature episodes.

Although IPCC projected global changes in temperature are typically presented in terms of global averages, more important for energy system vulnerability are changes for specific regions and in the form of episodic events. Such changes could be substantial (Solomon et al. 2007). Local temperature characteristics are of most practical concern because they represent the conditions that determine design and operating parameters and are, therefore, the parameters of concern to decision makers. These local temperatures are influenced by the combination of a more complex set of factors than global average temperature, including alteration of atmospheric and ocean circulation patterns (e.g., El Niño-Southern Oscillation, Pacific Decadal Oscillation, etc.), local and regional land use and aerosol changes, and global temperature trends. In this chapter, 'temperature,' unless otherwise stated, refers to the local air temperature at the location of the energy resource.

Fossil fuel resources are vulnerable to these changes in ambient temperatures in several ways. For coal, the vulnerabilities to increasing temperature are primarily associated with thermoelectric power generation and are twofold: reduction in generating efficiency and increase in power demand. The vulnerabilities to natural gas include those associated with coal but may also include the impacts of thawing permafrost and the subsequent impacts to resource extraction and transport in the Arctic. Petroleum is similarly vulnerable to thawing permafrost.

3.02.2.1 Thermoelectric Cooling: Reduction in Efficiency

Increasing ambient temperatures adversely affect the thermal efficiency of thermoelectric generating systems. This means that there would be an increase in fossil fuels consumption (almost entirely natural gas and coal) if average temperatures increase. The temperature effect impacts Rankine (steam) cycle plants and Brayton (combustion turbine) cycle plants. Rankine cycle efficiency is most sensitive to higher condenser temperatures (and pressures) that result from increases in ambient air and water temperatures. Brayton cycle efficiency is most sensitive to higher inlet air temperatures, which require increased work to compress the air prior to fuel injection and combustion. In addition, increases in ambient temperature can also reduce the power output of combustion turbines (Daycock et al. 2004;

Wilbanks et al. 2008). Wilbanks et al. (2008) suggest that increases in ambient temperature from summer to winter could lead to reductions in power output of about 1–2% for coal and nuclear plants, and Daycock et al. (2004) suggest that power output could be reduced as much as 3–4% for each 10 °F in ambient temperature for combustion turbines.

In the near term, thresholds for Rankine plants would most likely be in the form of discharge water temperature limits, which are in place to prevent significant changes in ambient water temperatures that can harm local ecosystems. The probabilities of reaching these limits is high in some areas, illustrated by the fact that there have already been instances where plants were required to reduce production to avoid exceeding discharge temperature requirements and more are expected (Averyt et al. 2011; Beshears 2007; O'Grady 2011). Over the longer term, measures to adapt thermoelectric power generation cooling systems to increasing ambient temperatures would likely be coupled with measures to adapt to changes in water availability, which will be discussed in more detail below.

3.02.2.2 Temperature-Driven Demand

At the same time, electricity demand is sensitive to higher temperatures due to increased use of air conditioning during hot days (Amato et al. 2005; Miller et al. 2008; Wilbanks et al. 2008). Higher temperatures lead to greater use of air conditioning and electricity demand, which is usually met with peaking units that tend to be less efficient than base load generating plants. In addition, because air conditioning load increases occur during the same high-temperature periods that lead to decreased thermal efficiency, the result is that peak loads can coincide with periods when the generating efficiency is at its lowest. Conversely, higher temperatures also reduce the winter demand for heating, which tends to reduce consumption of fossil fuels, particularly natural gas (Amato et al. 2005). However, it is important to understand that the relationship between temperature and energy use can considerably vary with location. A 2001 analysis estimated that a local annual average temperature increase of 2 °C would result in an increase of per capita electricity consumption of about 12% in Florida, but a decrease of about 7% in Washington, DC (Sailor 2001).

3.02.2.3 Thawing of Permafrost and Impacts to Infrastructure

Temperature changes have particular importance in the Arctic. This is because of the growing importance of the Arctic as a source of fossil fuels (Gautier et al. 2009; IEA 2011) and because average temperatures in the Arctic are forecast by some to increase much more than the global average (Anisimov et al. 2007). The Arctic is addressed here as distinct from the Southern Hemisphere polar regions for two reasons. First, there is considerable energy infrastructure and potential for additional development in Arctic regions (Johnston 2010). Second, there is no analogous development in the Antarctic, due to an international treaty prohibiting such development on Antarctica (Antarctic Treaty 1991) and to the comparatively small land mass south of 40° S latitude.

Rising Arctic temperatures would have a direct impact on the accessibility to onshore fossil fuel resources. Roads are built directly on permafrost in tundra regions. Because tundra is unable to support the weight of vehicles when thawing occurs at the surface, vehicle access is physically limited by the inability of the ground to support vehicle traffic. Access is also limited by regulations that designate conditions under which resource exploration is permissible to avoid permanent damage to the permafrost. As seen in Figure 2, the permissible days of exploration have dropped from 200 to about 100 days per year between 1970 and 2003 as temperatures have increased, making it increasingly difficult, if not impossible, to conduct effective exploration activities (Arctic Climate Impact Assessment 2004; Wilbanks et al. 2008). In addition, permafrost has been relied upon to support other key infrastructure, including the Trans-Alaska Pipeline System (TAPS). The TAPS design recognized the potential for degradation and even liquefaction of the ground supporting the pipeline, and design and operational measures have been incorporated into the system to avoid spills associated with subsidence caused by heating of the permafrost. A 2003 study noted that, while neither the TAPS operator nor the relevant regulatory authority considered permafrost degradation to be a problem, the design was based on a temperature history that covered one of the coldest 20 year periods in modern Alaskan history (U.S. Arctic Research Commission Permafrost Task Force 2003). The same study also noted that the oil and natural gas pipeline networks in western Siberia appear to be at even more risk to temperature-driven permafrost damage than the TAPS.

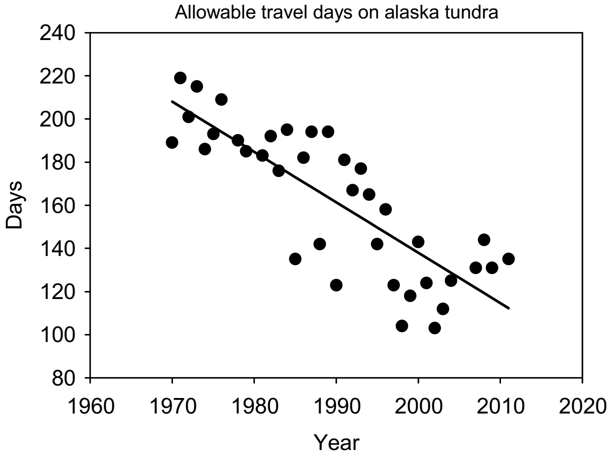

Figure 2 Decline in Alaska winter travel days from 1970 to 2011. Through 2003, opening dates reflect general travel opening. After 2003, opening dates reflect partial travel opening (Eastern Slope region). From Arctic Climate Impact Assessment, 2004: *Impacts of a Warming Arctic: Arctic Climate Impact Assessment*. Cambridge University Press, Petroleum News (2011): Off-road travel closes on North Slope. May 29, 2011, Petroleum News, Anchorage, AK. Retrieved February 17, 2012. [Available online at http://www.petroleumnews.com/pntruncate/230159208.shtml.]

3.02.2.4 Increased Access to Arctic Resources

Increasing temperatures in the Arctic would have a potentially beneficial impact on fossil fuel resources. The Arctic Climate Impact Assessment estimated that a reduction in Arctic sea ice could result in 90–100 navigation days per year (at 50% sea-ice concentration), or as many as 150 navigation days per year for ships with ice-breaking capacity in seas of up to 75% sea-ice concentration (Arctic Climate Impact Assessment 2004). Such an increase in navigable days (from the current 20–30 days at 50% sea-ice concentration) would greatly expand resource accessibility from sea routes. The combination of increased access by sea and difficulties with supporting onshore infrastructure cited above make it unclear if, or to what extent, temperature increases in the Arctic might enable increased offshore petroleum and natural gas production. Even so, there is a focused effort, particularly in Russia, to increase production and export of Arctic hydrocarbon resources, to the extent of the launch of the world's first ice-breaking oil tanker (Johnston 2010).

More generally, it is important to recognize that energy production in the Arctic is a clear example of the expansion of energy resource exploration and production into increasingly severe environments. While increasing temperatures have one set of impacts, decreasing temperatures have their own impacts. Colder temperatures or more severe storms (such as the one experienced in early 2012) can substantially hinder transportation and operations in the Arctic. Fossil fuel resources in the Arctic remain vulnerable to climatic conditions, whether warmer or colder, for which transportation and energy infrastructures are not adequately designed.

3.02.2.5 Responses/Recommendations/Thresholds

The extent of current understanding is not sufficient to identify a specific threshold beyond which responses to increased ambient temperature would need to be significantly different from current practices. However, operating plans and plant designs must be aware of the potential for long-term changes in the range of local ambient temperatures compared to historical averages. The primary approach to reducing the effects of temperature-driven demand is to improve energy end use efficiency in general (Wilbanks et al. 2008). Although this approach does not specifically address peak loads associated with temperature, it does reduce load in general, including peak load. Greater use of passive heating and cooling and more energy efficient building stock can specifically reduce space conditioning loads and use of demand-side management (DSM) that allows cooling systems to be cycled across a large portion of the affected distribution system and also allows some loads to be entirely shut down, which is also an adaptive approach to managing peak loads (Miller et al. 2008). Comprehensive approaches to DSM may be more effective if utility efforts are combined with government incentives or mandates (Carley 2011). These policies may take the form of energy efficiency incentives and changes to building codes to promote efficiency. Although DSM can result in lower total and peak demand, there remain challenges to broad implementation, including a need for improved metering and information infrastructure and changes in utility operational practices (Strbac 2008).

3.02.3 Weather Extremes

Weather extremes, such as severe tropical and other storms, intense precipitation events and flooding, and drought, can create vulnerabilities to the use of fossil fuels. A number of studies have indicated that the frequency and intensity of these events may increase as a consequence of changes in the global climate (Easterling et al. 2000; IPCC 2011). Observations suggest that there has been an increase in heavy precipitation events over the past several decades compared to earlier periods, albeit with strong regional variations (Gutkowski et al. 2008; IPCC 2011). However, there is also considerable uncertainty associated with these estimates and the impact of such changes, particularly with regard to magnitude of the changes, variability, and local impacts (IPCC 2011; Pielke and Wilby 2012). Even with these uncertainties, the IPCC recently reported that is it *likely* (The IPCC defines 'likely' as having a 66–100% estimated likelihood of the outcome) that, as a consequence of climate change, (a) the frequency of heavy precipitation will increase; (b) the maximum wind speed of tropical cyclones will increase; and (c) the 'global frequency of tropical cyclones will either decrease or remain essentially unchanged.' They also report that there is *medium confidence* (The IPCC defines 'medium confidence' as 'about 5 out of 10 chances' of occurring.) that (a) droughts will intensify in the twenty-first century and (b) there will be increases in heavy precipitation in spite of projected decreases in total precipitation in some regions (IPCC 2011).

Despite the significant uncertainties in future weather extremes there is a potential increase in risk due to increased precipitation, drought, and tropical cyclones as a result of climate change. It is, therefore, prudent to develop risk management strategies to address the vulnerabilities to fossil energy associated with weather extremes.

3.02.3.1 Drought

In many locations, the onset of drought conditions would exacerbate the shrinking gap between population-driven demand for water and water availability. The southwestern United States is a relevant example of these interactions. Even as an 11-year drought has reduced the levels of major reservoirs in the region, the population of the intermountain states (Arizona, Colorado, Montana, Nevada, New Mexico, Utah, and Wyoming) has increased by 20% since 2000 and is projected to increase nearly 40% more between 2010 and 2030 (Environmental Defense Fund and Western Resource Advocates 2010; U.S. Census Bureau 2005). Climate modeling indicates that conditions in the southwestern United States may become drier. In the event that the modeled results are realized, the resulting drought would add to the already growing stress on water resources (Environmental Defense Fund and Western Resource Advocates 2010). Even without such long-term trends resulting from human intervention in the climate system, the natural record of drought (e.g., such as the multidecadal drought in the western United States in the sixteenth century) already suggests that the threat of prolonged dry periods is significant (Meko et al. 2007).

More immediately, the Electric Reliability Council of Texas (ERCOT), operators of the electrical grid in Texas, recently released an assessment that indicated a potential shortage of more than 1000 MW of power during the winter of 2011–12 if the drought in Texas had continued unabated, even if load levels and unit outages remained at historical levels (ERCOT 2011). In addition to lack of water availability due to drought, reduced river flow in drought conditions can also lead to restrictions on thermoelectric cooling water discharges, as was seen in Europe during the 2003 heat wave (Fink et al. 2004; Förster and Lilliestam 2010).

3.02.3.1.1 Competition for Water Resources

More broadly, increasing populations and growing demand for energy will increase competition for water resources. Thermoelectric power generation accounted for 41% of all withdrawals of fresh water in the United States in 2005, more than any other sector (Kenny et al. 2009). Although a small fraction of the withdrawn water is actually consumed (e.g., not available for further use), thermoelectric power generation requires large volumes of water to operate (USDOE 2006). Drought conditions can, therefore, be a source of vulnerability for fossil-fueled power steam plants, in addition to the temperature vulnerabilities noted above. In the event that carbon capture systems are used for fossil-fueled plants, the water demands could substantially increase (Zhai and Rubin 2010). The need for large volumes of water for conventional cooling systems could limit the location of future fossil-fired power plants, particularly in regions that are projected to face greater vulnerability to drought driven by climate change.

Production of natural gas using hydraulic fracturing requires significant amounts of water for the fracturing process. Volumes of required water vary from about 3 million to 8 million gallons per well completion, depending on specific well conditions (Bene et al. 2007; Hazen and Sawyer 2009). Some estimates of well completion activity indicate that the fraction of groundwater used for hydraulic fracturing could reach near 50% of total groundwater withdrawals. In locations vulnerable to drought, such levels of water use could adversely impact the viability of gas production from tight formations.

Unconventional sources of petroleum could also be adversely impacted by drought. A recent study estimated that transportation fuels produced from coal, natural gas, oil shale, or tar sands could require 150–270% more water per gallon of fuel produced than conventional petroleum-based gasoline (King and Webber 2008). Because many of these resources are located in areas vulnerable to drought, water availability problems have the potential to make these proposed approaches to liquid fuel production nonviable. Much of the analysis related to these unconventional fossil fuel resources, particularly for development in the western United States, was conducted 30 or more years ago, and growing populations and other demands for water in the interim have made it difficult to evaluate the validity of those earlier studies (Bartis et al. 2005). In the event that long-term average precipitation levels were to fall, the stresses on regional water resources would increase, further limiting the ability to produce these unconventional energy resources.

3.02.3.1.2 Energy Requirements for Constrained Water Supplies

Drought would also be likely to increase the amount of energy that is required to meet the demand for water in afflicted regions. A 2002 report by the Electric Power Research Institute estimated that the electricity required for supplying treated water in the United States would closely track population growth, which resulted in a projection that the fraction of electricity required for water supply and treatment would remain relatively constant at about 4% of total generation (EPRI 2002). However, this assumes little fundamental change in water resources. In the event that there are significant water shortages due to drought, the energy required to supply and treat water could substantially increase, perhaps as much as a factor of four times more energy per unit volume of water (Environmental Defense Fund and Western Resource Advocates 2010). Such increases would be expected to be regional rather than national but have the potential to add to the demand for fossil-fueled electricity.

3.02.3.2 Flooding; Infrastructure Vulnerability

The proximity of numerous power generation facilities, mines, roads, railroads, and other energy-related infrastructure to rivers, combined with the multidecadal operational lifetimes of those facilities, makes it crucial to account for the potential vulnerability of energy-related facilities to floods. As examples, the floods across eastern Australia in late 2010 through early 2011 resulted in an estimated reduction of 15 million tonnes of coal output (ABARES 2011) and the 2010 Pakistani floods were estimated to have knocked nearly 15% of the country's electricity generating capacity off line (Kronstadt et al. 2010). Although an increased frequency of heavy precipitation events implies increases in local flooding, differences in regional and local factors result in complex relationships between precipitation and flooding, leading to the IPCC forecasting with *low confidence* (The IPCC defines 'low confidence' as having 'about 2 out of 10 chances' of occurring) that fluvial flooding would increase in general as a consequence of climate change (IPCC 2011). Even so, the same IPCC report assumes that, based on physical reasoning, there is medium confidence that local flooding would increase.

3.02.3.3 Storm Intensity and Frequency

Experience with Hurricane Ivan in 2004 and Hurricanes Katrina and Rita in 2005 demonstrated the vulnerabilities of offshore petroleum production to powerful tropical storms (see Figure 3). Over 100 production platforms were destroyed and more than 600 pipelines were reported damaged in the Gulf of Mexico by the two 2005 storms (Det Norske Veritas 2007). The loss of production capacity and damage to other energy infrastructure caused by these two storms is estimated to have cost $15 billion in direct losses, not including restoration and

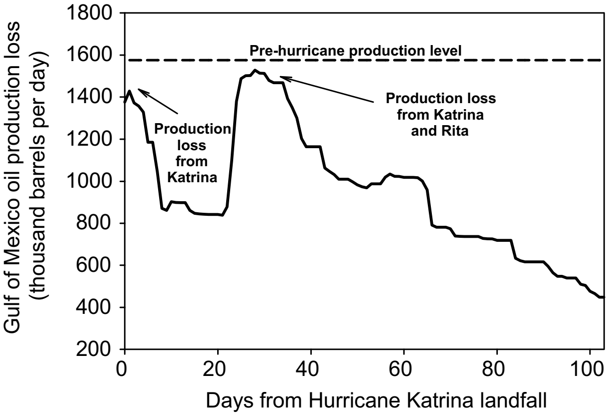

Figure 3 Loss of petroleum production due to damage from Hurricanes Katrina and Rita. From Energy Information Administration (2005): Hurricane Impacts on the U.S. Oil and Natural Gas Markets. Washington, DC, U.S. Department of Energy, Energy Information Administration.

recovery costs, or the direct and indirect costs of higher prices to consumers (Wilbanks et al. 2008).

In addition to damage to production infrastructure, US refining capacity is also highly vulnerable to damage from tropical storms, with nearly 45% of crude oil refining capacity located in Louisiana and Texas, primarily along the coast of the Gulf of Mexico (Energy Information Administration 2011a). The consequences of such concentration of refining capacity in an area prone to tropical storm damage were clearly seen following the impacts of Hurricanes Katrina and Rita (Hibbard 2006; Parfomak 2008; Wilbanks et al. 2008). The vulnerabilities to storm damage go beyond direct impacts to refineries to include the potential for reduced output as a result of loss of electric power caused by damage to electric generating plants or transmission lines (Peters et al. 2006).

There has been considerable study of the potential impact of climate on the intensity and frequency of tropical and other storms. Although there is general agreement that a warmer global climate would increase atmospheric and sea surface temperatures and the amount of water in the atmosphere (Solomon et al. 2007), which are associated with more powerful storms, there remains substantial uncertainty about the ultimate effect on storm frequency and intensity (Gutkowski et al. 2008; IPCC 2011).

3.02.3.4 Responses/Recommendations

It is reasonable to view Hurricanes Katrina and Rita as threshold events that demonstrated actual, as opposed to probable, vulnerability to intense storms. Following the 2005 storms, efforts were made by industry to develop improved standards for offshore platforms (American Petroleum Institute 2005) and to improve capabilities to repair damaged undersea pipelines (Bicker 2010), which were demonstrated during the Macondo oil spill in April 2010. These efforts can help reduce vulnerabilities to tropical storm events, but can in no way eliminate them. The concentration of energy infrastructure along the US Gulf Coast (or elsewhere) is even more difficult to address, given the enormous capital investments in existing infrastructure and the long time frames associated with development of new infrastructure. A recent study identified policies that could be applied to encourage geographic dispersion and infrastructure recovery from disruptions, but noted that such policies are not without their own risks (Parfomak 2008).

The vulnerabilities to weather extremes discussed here are primarily related to infrastructure. The approach to minimizing the impacts of weather extremes is generally twofold. The first and most important step is to consider the potential range of extremes (e.g., temperature, flooding, and drought) that may be experienced over the lifetime of the facility or system and to design the facility or system to minimize the risks associated with the relevant extremes. Although the focus here has been on infrastructure, it is crucial for designs to protect workers and the public from harm due to extreme weather events. The second step is to develop and implement effective emergency response plans to guide responses in the event of weather extremes. Effective design and planning can mitigation long-term impacts associated with extreme weather events.

3.02.4 Sea Level Rise

A rise in the mean sea level represents a vulnerability to facilities and infrastructure located along coastlines. The risk associated with sea level rise is magnified by the fact that major impacts of coastal inundation are experienced as a consequence of high tides and storm surge. The combination of more intense tropical storms and higher base sea level could result in significantly greater coastal areas being subject to higher levels of inundation than have historically occurred.

There is general agreement that the observed rise in mean sea level between 1961 and 2003 would continue if global temperatures increase, caused by melting land ice and the thermal ocean expansion (Bindoff et al. 2007). The IPCC's recent report on managing risks of extreme events predicts that it is *very likely* (The IPCC defines 'very likely' as having a likelihood of 90–100% probability of occurring) that increasing sea level will contribute to 'upward trends in extreme coastal high water levels in the future' (IPCC 2011). The IPCC predicts mean sea level to rise between about 0.2 and 0.6 m in the last decade of this century (Meehl et al. 2007). The IPCC predictions for sea level rise do not include substantial contributions from loss of ice from the Greenland or Antarctic ice sheets. These predictions have been questioned since the publication of the IPCC's Fourth Assessment Report, with some studies hypothesizing that ice sheet loss could increase the magnitude of sea level rise by the end of the century by a factor of 2–3 (Nicholls et al. 2011; Rignot et al. 2011).

3.02.4.1 Infrastructure Vulnerability

The vulnerabilities to sea level rise are similar to those noted above for flooding. Fossil plants, refineries, fuel loading ports, and related infrastructure located in coastal areas would be vulnerable to higher sea levels and to inundation during extreme weather events such as tropical storms. Higher sea level will, therefore, likely increase vulnerability to these events for facilities in coastal areas. Sea level rise would not add to risks for those facilities that are located away from coastal regions, although loss of coastal facilities, even on a temporary basis, would be expected to increase the stress on unaffected capabilities (as would also be the case for weather extremes separate from sea level rise). An additional risk related to sea level rise is the increased potential for increased ocean front erosion. This could be a factor in the stability of transport infrastructure (roads, pipelines, etc.) in particular. Although it would generally be expected that any impacts would be relatively short term, there may be situations where loss of bridges or other major infrastructure components could result in much longer term impacts.

The probability of continuing sea level rise is considered to be high, as noted above. However, the probability of abrupt and major sea level rise, as has been suggested as a result of major collapse of ice sheets, appears at this point to be low, although the uncertainties of such events are substantial. There is not expected to be a specific point at which sea level rise is generally 'too high,' given the site-specific factors that determine vulnerability. It is more likely that there would be a threshold event, such as a tropical storm combined with high tides and a general rise in sea levels that would be identified after the fact, similar to the situation with weather extremes. The adaptation measures applicable to weather extremes and concentrated infrastructure hold for sea level rise as well, but may need to be supplemented with measures such as construction of sea walls. The recent disaster at the Fukushima nuclear plant highlighted the need for emergency systems, particularly emergency generators designed for inundation levels higher than those for the plant as a whole in the event that the sea wall was breached (Buongiorno et al. 2011). The massive flooding in Pakistan in 2010 (although not associated with sea level rise) and the resulting damage to the country's power generation capacity similarly illustrates the need to design energy infrastructure for resilience with respect to high water conditions in areas prone to sea level rise (Kronstadt et al. 2010).

3.02.5 Mitigation Strategies

Studies calling for reductions in CO_2 emissions from energy produced by fossil fuels as a means to address climate change first appeared in the mid-1970s (Marchetti 1977; Schneider and Dennett, 1975). The emphasis on global-scale GHG mitigation has grown in scope and contention, with many strongly stating that major mitigation measures are of the essence (IEA 2008, 2011; Princiotta 2011) and others questioning the need for such major changes to the world energy system and economy (Lomborg, 2001). Although a strong focus of many mitigation strategies is a shift toward nonfossil energy sources (e.g., wind, solar, nuclear) and a major effort to reduce energy demand in general, many (if not most) proposals continue to include fossil fuels as part of a strategy for reducing GHG emissions to levels considered necessary to avoid the most severe predicted impacts on climate from the addition of GHGs (Meinshausen et al. 2009; Rogelj et al. 2011). Any large-scale implementation of GHG mitigation strategies would substantively change the role of fossil fuels in the world energy mix with a general trend of 'decarbonization;' that is, moving toward less carbon-intensive fuels and technologies such as natural gas, coal with carbon capture and sequestration (CCS) systems, and vehicle electrification (IEA 2008; Pacala and Socolow 2004). Such changes would emphasize different vulnerabilities for different fossil fuels, presenting both opportunities and challenges.

3.02.5.1 Rate of Change in Energy System: Introduction of New Technologies and Practices

In general, GHG mitigation strategy proposals call for major, and relatively rapid, changes in the global energy system. In the near term, the lack, but continuing consideration, of binding global and national commitments to significantly reduce GHG emissions creates great uncertainty for those faced with making investment decisions for new energy infrastructure (Bergerson and Lave 2007; Patiño-Echeverri et al. 2009). Over the longer term, major changes in the energy infrastructure would be likely to increase system complexities by incorporating a much higher fraction of intermittent electricity generation sources, tighter links between the energy and agricultural sectors through increased use of biomass, and the addition of CO_2 transmission networks. The more rapidly these complexities are added, the more vulnerable the system is to unforeseen problems. Although it is questionable how quickly the energy system could be transformed (Kramer and Haigh 2009; Smil 2010), increasing the complexity and the rate of change in the energy system would represent a source of vulnerability to fossil and other energy sources.

3.02.5.2 Backup for Intermittent Generation Sources

One of the added complexities of a low carbon electricity generation system would be the intermittent nature of many existing renewable resources, particularly wind and solar energy. Because of their inherent intermittency, other demand dispatch-capable generating resources that can match demand and balance load characteristics – largely fossil-fueled generating systems – need to be maintained as backup for renewable resources. Renewable resources can reduce the total fossil-fueled power generation but may not reduce the required generating capacity (Hannes 2009). Indeed, there are estimates that fossil-fueled generating capacity may need to increase, even if total fossil-fueled generation decreases (Gowrisankaran et al. 2011). The combination of level or increased capacity (likely with short start-up or load ramping times) and lower overall utilization means that capital costs are likely to become a larger component of total cost of electricity for fossil-fueled units. This also complicates decisions related to maintenance and operational life.

3.02.5.3 Natural Gas and Potential for Methane Emissions

Natural gas is seen as a key component of many strategies to reduce GHG emissions from energy production and use. This is because of the significantly lower carbon content of the main component of natural gas (methane) and because of the ability of natural gas to be used in combined cycle generating plants that can reach considerably higher thermal efficiencies compared to Rankine-cycle steam generating systems. Until recently, a major concern regarding this approach was the limited global supply of natural gas. In the past several years, this concern has been greatly reduced with the increasing use of hydraulic fracturing and its ability to extract what is referred to as 'unconventional' natural gas from formations previously considered uneconomical to develop (Kerr 2010). More recently, there has been considerable controversy focused on the potential for substantial increases in GHG emissions due to the much higher level of methane emissions that can be released during completion and maintenance (called 'workovers') of unconventional natural gas wells (Howarth et al. 2011; Stephenson et al. 2011). Unconventional natural gas production has been highly controversial for other environmental reasons, largely associated with impacts to groundwater (Osborn et al. 2011). The vulnerability to natural gas related to climate, however, is largely related to fugitive methane emissions, which (in most cases) can be controlled using relatively straightforward available technologies.

3.02.5.4 Increased Rate of Utilization with Carbon Capture Energy Penalty

In addition to switching to natural gas, many CO_2 mitigation strategies propose use of technologies that capture CO_2

generated by fossil-fueled electricity generating plants and sequester it. There are two main approaches to CCS technologies – pre- and post-combustion systems. Pre-combustion system designs generally employ highly oxygen-enriched air (90% or more O_2) in combustion or gasification processes. These oxyfuel combustion systems are designed to burn coal or natural gas with oxygen that would generate a high-CO_2 exhaust gas that could be compressed and sequestered, potentially without extensive additional treatment. Oxygen-based gasification systems generate a high-hydrogen fuel for use in combined cycle systems that have essentially no CO_2 in the exhaust. Current post-combustion designs rely on amine-based scrubbing reagents to capture the CO_2 and then release it during reagent regeneration. These designs typically require substantial reheating of the flue gas. Both pre- and post-combustion carbon capture designs therefore require large amounts of heat and electrical energy, which would decrease the net power generation for the same amount of fuel input. While additional energy would be needed to compress, transport, and inject the captured CO_2, that energy is small relative to the energy needed for the carbon capture processes. Estimates of the efficiency penalty are in the range of about 15–25% or about 5–10% points, depending on the plant design (House et al. 2009; Rubin et al. 2007). Conventional pulverized coal systems would suffer the largest penalty, with integrated gasification combined cycle systems having the lowest efficiency penalty for CCS.

The vulnerabilities to fossil fuels from broad adoption of CCS are threefold. First, the significant reductions in efficiency mean that greater amounts of coal or natural gas would be required to generate the same amount of net electricity. This would increase the rate of resource depletion and would also increase the environmental impacts of the extraction processes. Second, the demand for water would increase because of both the lower net thermal efficiency and because (for post-combustion systems) CCS process designs now depend on substantial amounts of water in addition to that for thermoelectric cooling (Ciferno et al. 2010). The third vulnerability is that the cost of electricity from fossil-fired plants would increase, due to greater capital investment requirements as well as increased operating costs, which would make nonfossil alternatives more attractive. It is also possible to view CCS as increasing the potential use of coal in particular, in the event that GHG emission limitations were to be implemented, as the process would substantially reduce the emissions of CO_2 from coal-fired power generation.

3.02.5.5 CCS Geological Storage Risks

Once the carbon is captured, it would need to be sequestered to remove it from the carbon cycle. Injection of compressed CO_2 into underground geological formations, such as depleted petroleum reservoirs or deep saline aquifers, is currently considered to be the most likely method and has been demonstrated at large pilot scale. Such efforts would not be without risks, including risks associated with CO_2 leaks into the atmosphere, contamination of groundwater resources, or induced seismicity (Wilson et al. 2007). Although the US Department of Energy has developed a research and development roadmap that recognizes many of the risks related to geological sequestration, fossil-fueled power generation systems would remain vulnerable to these as well as legal and financial risks, particularly the issue of long-term liability for sequestered CO_2 (USDOE 2007).

3.02.5.6 Increasing Electrification of Transportation System

While increased cost of electricity will tend to reduce demand, the growth of electric-capable vehicles, including all-electric and plug-in hybrid electric vehicles, will act to increase electricity demand. This increased demand, if it substantially increases, would likely have its own load pattern, typically expected to be opposite of the current daytime peak, since it is generally believed that electric vehicles will recharge at night when total demand (and rates) are lower. However, there would also be the potential to 'impact the overall system reliability when the entire infrastructure is used near its maximum capacity for long periods,' according to one study (Kintner-Meyer et al. 2006). The study also noted that, if the current cyclical load patterns were to change such that base loads were largely constant over a 24-h period, maintenance scheduling could be more difficult. Conversely, it has been noted that significant vehicle electrification could serve as a very large electrical energy storage system if grid controls and capabilities are in place. The highly dispersed battery capacity in such a situation has been proposed as a means to store intermittent renewable electricity and to provide a stabilizing influence on grid operations (Kempton and Tomić 2005).

3.02.6 Adaptation

Measures taken in response to climate can also create vulnerabilities for fossil fuels, even if those measures are implemented in areas other than energy. Adaptation measures may include responses to drought such as the need to transport water greater distances or employ desalinization systems, both of which will increase the demand for energy now largely supplied by fossil fuels. Relocation of infrastructure away from areas that are increasingly prone to flooding has the potential to disrupt operations of pipelines, power plants, refineries, and other energy system components. Shifts in populations to cooler climate zones or away from flood zones would lead to changes in transportation energy needs or electricity demand patterns. Similarly, if agricultural regions shift toward more favorable growth zones, the transportation infrastructure and possibly energy requirements could also shift.

The impacts to fossil fuels of other adaptation measures have been discussed above. These include increased air conditioning load and the potential for ensuring adequate water supplies using more energy-intensive measures. In both cases, the vulnerability to fossil fuels is an increased rate of resource consumption.

One issue that was not addressed in the above discussion of increased temperature is the potential for greater formation of tropospheric ozone. There is a recognized link between increased temperatures and increased formation and concentration of tropospheric ozone (Weaver et al. 2009). To the extent that climates become hotter, tropospheric ozone concentrations are likely to increase, although the links between climate (which involves more than simply temperature change) and ozone formation are more complex than a simple linear relationship between temperature and ozone (Jacob and Winner 2009; Steiner et al. 2010). Even so, in instances where air quality problems worsen as a consequence of climate, the adaptation measure needs to be able to reduce anthropogenic sources of ozone precursor emissions, particularly nitrogen oxides, much of which are emitted by the combustion of fossil fuels. This pressure could expand the need for pollution control technologies and strategies, which could impact the use of fossil fuels.

3.02.7 Social Impacts

Vulnerabilities of fossil fuels to climate are not entirely related to direct physical climate impacts or changes in technology, but also include what are broadly defined here as 'social impacts.' These can include corporate and personal behavior and perspectives or political instability that may be caused by or exacerbated by changes in climate.

3.02.7.1 Changes in Personal and Corporate Behaviors

Personal and corporate behaviors related to energy could result in reduced demand for fossil fuels as people and organizations respond to changes in climate. Voluntary measures, such as reducing heating, ventilating, and air conditioning energy consumption, purchasing more fuel efficient vehicles, or greater use of public transportation can have significant impacts on energy consumption. Although these changes may be primarily driven by increases in energy prices (Busse et al. 2009), changes may also be motivated by other than explicit economic factors (the converse is also true – individuals and organizations may also opt to take no action, even when action can be economically profitable). The McKinsey study, 'Pathways to a Low-Carbon Economy' identified significant financial savings and GHG reductions due to behavioral actions to reduce energy use (McKinsey and Company 2009), even in the commercial and industrial sectors, which would be expected to have the technical and financial wherewithal to take advantage of efficiency opportunities.

The extent to which behaviors pose vulnerabilities to fossil fuels is uncertain. On the one hand, it is possible to argue that reduced consumption can harm the financial health of the fossil fuel industry. On the other hand, considerable resources are being applied by electricity generating firms to enable individual and corporate consumers to reduce consumption, particularly during periods of peak demand, which can help utilities avoid or delay the need to operate – and finance – peak generation equipment or purchase additional expensive peak power from other generators (U.S. Department of Energy 2006).

3.02.7.2 Siting Energy Infrastructure

There are many connections between technological systems (that tend to be the focus of technical and policy development) and social and political 'systems' such as communities, citizen groups, and political organizations that can greatly influence the success of technological strategies. If the concerns of these social systems are not adequately recognized, understood, and addressed, the vulnerability of technological approaches to delay or increased cost from political or legal challenge substantially increases. Siting of energy infrastructure, including energy extraction, pipelines, generating plants, or carbon storage facilities, can be one of the more difficult practical barriers to the development, demonstration, and deployment of energy system components.

Switching from coal to natural gas has been considered as an important component of GHG mitigation strategies (IEA 2008; Pacala and Socolow 2004). Recent advances in natural gas production technologies, particularly the combination of hydraulic fracturing and horizontal drilling, have substantially increased proven natural gas reserves. However, the use of hydraulic fracturing has become highly controversial due to concerns about the potential environmental impacts of the process. Although the controversies are most visible in the general news media, citizen group websites, and even documentary films, they are also debated in the scientific literature (Davies 2011; Osborn et al. 2011; Schon 2011). These concerns are serious enough that there are active efforts to ban the use of hydraulic fracturing in some localities, despite the potential for significant personal and community economic benefit (Tavernise 2011).

Public concerns also impact the ability to develop and demonstrate CCS technologies, a critical component of most comprehensive GHG mitigation approaches. There are examples of local-, state-, and even federal-level agencies refusing to allow carbon sequestration projects to move forward because of public opposition (Brown et al. 2011; Kanter 2011).

Although there is a tendency for technical and policy experts to simply attribute such opposition to a 'not in my backyard' attitude, there are approaches that can be taken to address public concerns. The public concerns are often different from those perceived by the technical and policy experts, indicating that different communication and outreach approaches are needed to develop beneficial relationships with the communities and other social organizations that are impacted by energy infrastructure (Bradbury et al. 2009; Oltra et al. 2010; Wong-Parodi et al. 2011). Although there is extensive research and literature on the need for public engagement in the development and use of energy-related science and technology, there often seems to be much less application of that understanding in practice.

3.02.7.3 Political Instability

Political instability and conflict in major oil-producing regions have long been seen as sources of vulnerability to petroleum supplies. Conflicts in the Middle East, in particular, have repeatedly demonstrated that world oil prices, and in some instances, availability, are subject to disruption during times of conflict. Already-tight supplies of water in the Middle East will be increasingly stressed by growing populations. Changes in precipitation patterns, combined with existing political tensions and water demands, could easily increase the chances of conflict, with a substantial potential for petroleum supply disruption (Chin 2008; CNA 2007; Gleick 1989). Conflict and instability are not restricted to the Middle East or other regions of historical concern. There is also a growing potential for conflict over Arctic resources that could impact fossil energy resources particularly if those resources become more accessible, as discussed above (Johnston 2010; O'Rourke 2011).

3.02.8 Systemic Impacts

Changes to the global energy system in response to climate and energy security concerns and the increasing technical challenges of accessing fossil energy resources have led to greater complexity in the system. A greater emphasis on biofuels in the United States, for instance, has more closely tied the stability of the US transportation fuel supply to the uncertainties in agricultural output that are strongly influenced by changes in precipitation and temperature. The extent to which, and the rate at which, the energy system, including fossil fuels, will be required to change to mitigate GHG emissions can increase the potential for unforeseen problems and vulnerabilities.

3.02.8.1 Increasing Electrification: Pressures on Generation, Transmission, and Distribution

Increasing electrification of light-duty vehicles is seen as a key component of a comprehensive GHG mitigation strategy, as well as a means to reduce dependence on imported petroleum. A major shift toward electrified vehicles, as noted above, can place greater pressures on generation, transmission, and distribution systems. It is unclear whether the transportation system is at greater risk due to reliance on long, and often politically uncertain, petroleum supply chains compared to increased electrification of the vehicle fleet.

3.02.8.2 Shifting Toward Petroleum if Alternatives are not Successful

One vulnerability faced by fossil fuels is the potential for greater petroleum demand, should renewable fuel or electrification options fail to displace petroleum as much as expected. Although this vulnerability may also apply to electricity generation, it may be most pressing for transportation fuel. In 2009, ethanol production in the United States reached 10.6 billion gallons, compared with the consumption of 127 billion gallons of gasoline (Energy Information Administration 2011b; RFA 2011). A significant drop in ethanol production, conceivably due to climate-related reductions in feedstock production or disruption in transport due to flooding, could place considerable stress on the gasoline production infrastructure in the United States. A recent analysis estimated that the use of ethanol resulted in US retail gasoline prices being lower by an average of $0.89 per gallon in 2010 (Du and Hayes 2011); it is tempting to presume that major reductions in the availability of ethanol would increase retail gasoline prices the same amount. Even if such a presumption were to be accurate (which is questionable), transportation fuel shortages have significant costs to the economy beyond higher fuel prices.

3.02.8.3 Technological Change

More generally, major changes to the energy system designed to lower carbon emissions in a relatively short period of time could increase risks due to unforeseen consequences of those changes. It is recognized that technical failures often accompany innovation, often because innovation often moves technological systems beyond well-developed design and operational experience (Chiles 2001; Petroski 1992). Although technology developers work to create systems that are robust, the relatively rapid introduction of new technologies and the increasingly tight coupling of complex systems (e.g., agriculture and energy, water and energy) can combine to have unforeseen impacts, both beneficial and adverse. The nature of unforeseen events is such that they are impossible to specifically address *a priori*. Even so, it will be important to develop systems for both fossil and other energy resources that are as robust as possible as the transition to a low-carbon energy system progresses.

3.02.9 Conclusions

To many, the greatest vulnerability of fossil fuels to climate is a shift toward a carbon-constrained energy system. There are calls for, and analyses of, global efforts to achieve significant carbon emission reductions, including reductions to zero net carbon (DeCanio and Fremstad 2011; Jacobson and Delucchi 2011; Kharecha et al. 2010). The practicality of such reductions to be achieved in practice due to technical, economic, social, or political barriers remains an open question, but one that has generated enormous political and public debate.

Regardless of the status of national or global efforts to reduce carbon emissions, fossil fuels are also vulnerable to changes in climate and the ensuing impacts to resource production. Because fossil fuels will necessarily continue to be a part of the global energy system for the foreseeable future, it is important to understand those vulnerabilities that are driven by climate in addition to its other environmental and social vulnerabilities. Changes in temperature and precipitation patterns could necessitate changes in fuel production practices and, potentially, accessibility to resources. The impacts of environmental change more broadly have a strong potential to exacerbate existing, or lead to new, political tensions that can impact the production and transport of fossil resources. These conditions, now considered to be anomalies, may well become conditions that need to be addressed on a continuing basis.

The growth of international trade, tighter connections between different components of the global energy system, and an increasing emphasis on development of sustainable practices will bring a greatly expanded emphasis on understanding system-wide and life cycle impacts of corporate, national, and international strategies regarding the production and use of fossil fuels. Questions regarding the life cycle emissions from natural gas and life-cycle GHG comparisons between petroleum and biofuels are two examples of the growing policy relevance of life cycle analysis, particularly with regard to GHG emissions and climate response policies. The 'Green Book' recently released by the National Research Council recommended that the US Environmental Protection Agency incorporated sustainability concepts (i.e., a bottom-up vulnerability perspective) into its policy development and implementation (National Research Council 2011). The growing trend toward addressing problems from a sustainability perspective will increase the need for understanding the combined environmental, economic, and social impacts associated with issues such as energy production and use that have previously been evaluated from perspectives that were narrowly focused on individual technical, economic, or environmental factors.

For most of the issues addressed here, there are few, if any, distinct physical thresholds that will clearly define a transition from one set of conditions to a 'new normal.' In many instances, thresholds may be organizational rather than physical, as organizations perceive the need to prepare for changes in conditions associated with climate, or as financial, legislative, or regulatory requirements require organizations to take action in response to changing conditions (Lehmann 2011). Regardless of whether there are physical, organizational, or no thresholds, the impacts of climate can create additional factors that will impact the ability to develop and use fossil fuel resources. It is important to remain aware of how conditions are changing and how they are expected to change as decisions about long-term investments are developed.

Recommendations for those charged with decision making related to fossil fuels fall into four categories: holistically managing resources, designing for future conditions, taking a systems perspective, and expanding stakeholder interactions. These recommendations are not new, but are often set aside in the interest of short-term expediency. Thus, the most critical recommendation may be to recognize that these factors are becoming increasingly important to the success of long-term strategies related to fossil fuels.

3.02.9.1 Managing Resources Holistically

Resources need to be managed as closely connected systems in ways that recognize and address the connections between them. Integrated resource management, particularly with regard to water and energy, is becoming an increasingly common practice as the demand grows for both energy and water. Water utilities have long recognized the need to reduce energy consumption in their operations, and there is a growing understanding of the importance of water to electricity generators. Both communities are gaining an appreciation that saving water saves energy and saving energy saves water. DSM strategies in the electric sector not only reduce the need for additional peak generating capacity, but also help to conserve water needed for base load generation. Although water and energy issues are most commonly addressed by separate management, legal, and regulatory structures, there is increasing interaction across those structures as the impacts of climate and other environmental effects become more apparent. Such interactions need to become the norm.

3.02.9.2 Forward-Looking Design

The design of fossil energy infrastructure, from production through use, must be based upon expected environmental conditions of the next several decades, which may be considerably different from the past several decades. The expectation that energy infrastructure investments, including support infrastructure such as transportation, will operate over several decades illustrates the importance of designing for the envelope of plausible future conditions. Greater variability in temperature and precipitation, including extremes, and the potential for substantive changes to regional weather patterns, would represent a 'new normal' environment for infrastructure. Long-term drought and an increased frequency of severe weather and floods can each impact the production and use of fossil fuels. Decision makers must recognize the possibility of operating in these changed conditions, and develop designs, operating strategies, and financial plans that account for such changes.

3.02.9.3 Taking a Systems Perspective

Future development and use of fossil fuels must be understood as part of the broader, more complex energy, social, and economic system. The impacts of climate on fossil fuels illustrate the need to consider these energy resources in a broader systems context. The connections between energy and water, the interactions between renewable fuels and fossil fuels, and a growing awareness of the life cycle effects of energy production and use each illustrate the fact that it is no longer possible to isolate the economics, environmental effects, or the technological developments associated with fossil fuels from other energy resources or from socio-economic influences more generally. Although physical fossil fuel resources may not be impacted by climate, the ability to extract, process, and use them is impacted, often in ways that are not immediately apparent. For example, high temperatures could reduce yields of biofuel feedstock, leading to increased demand for, and price of, gasoline. While it has long been recognized that higher oil prices contribute to higher food prices, it is only recently been recognized that oil prices could be impacted by crop production.

The rate at which these changes are being made adds to the potential vulnerability of fossil energy resources. Rapid and extensive changes in technologies can lead to unforeseen problems (whether connected with the technology or not) that can create additional opposition to the changes. Recent examples include the increased application of hydraulic fracturing and the effort to evaluate geological carbon sequestration. In both cases, it is important to understand the broader systems context (technical, social, and economic) in which fossil fuels are developed and used.

3.02.9.4 Expanding Stakeholder Interactions

Substantive interactions with communities and other public stakeholder groups must be a basic component of fossil fuel development efforts. The need for organizations to interact with the public on the issue of development and use of fossil fuels has considerably increased with the growing understanding of the connection between fossil fuels and climate. Other issues, such as the impacts of coal mining, the concerns about the potential for hydraulic fracturing to impact water resources, and the Deepwater Horizon accident and spill, have raised the public visibility of the environmental impacts of fossil fuel production. These interactions need to go beyond providing technical and economic information, but need to acknowledge that public perceptions of technical issues are often strongly influenced by factors that are seemingly unrelated to the immediate issue. It is likely that dedicated expertise and resources will be needed to effectively respond to social perceptions and concerns that can have substantial influence on the ability to implement plans for developing or using fossil fuel resources.

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3.03 Renewable Energy Resources – Onshore/Offshore Wind Energy

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Glossary

Atmospheric boundary layer The lowest part of the atmosphere where all of the meteorological phenomena that directly affect wind turbines are taking place.

Numerical Weather Prediction (NWP) Quantitative forecasts for all basic meteorological variables that fully characterize the weather, as produced by complex numerical models solving sets of differential equations on a three-dimensional spanning for a given region (and up to the whole globe) and the atmospheric boundary layer.

Reanalysis Based on all available meteorological observations at any given time, the reanalysis is an estimate of the state of the atmosphere at this time, as filtered through a dynamic model of the atmosphere (similar to those for producing NWPs).

Wind atlas Maps summarizing the assessment of the wind energy resource for any point over a region of interest. They may be produced based on linearized models, e.g., WAsP, or with more advanced approaches relying on some of the mesoscale models used for producing NWPs.

Wind power penetration Share of wind energy in the energy mix that allowed meeting the electrical demand for a country or a region, at a given time or over a period of time.

3.03.1 Introduction

Among the various forms of existing renewable energy sources, wind power has recently been the most successful, in terms of capacities deployed worldwide, but also in terms of its integration into existing power systems and electricity markets. Some of the historically leading countries in giving a prime importance to wind in their energy mix, that is, Denmark, Spain, and Germany, have reached significant levels of their electricity demand met by this renewable energy, either in absolute terms or relative to the electric demand itself, as quantified by the so-called wind power penetration. For instance in Denmark, wind energy generation allows fulfilling the overall needs in electricity of the whole country over a number of hours per year already, while it covers more than 20% of the electrical load on average over the last few years. Even though almost all wind turbines were installed onshore until the recent past, the trend today is to develop large-scale offshore wind farms (up to several GWs), owing to better wind conditions and space availability. Taking the example of Northern Europe (around the North Sea, Baltic Sea, and Irish Sea), most of future new wind farms are planned offshore, while the increase in onshore wind capacities is at least partly due to repowering, i.e., to the decommissioning of old turbines

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and replacing them with newer more powerful ones. This justifies discussing wind energy in both the onshore and offshore cases, in view of the meteorological characteristics of the wind resource and of the technological aspects involved. A more lengthy discussion of the respective characteristics of onshore and offshore wind energy is available in EEA (2009), while a status report on the offshore wind energy developments was recently released (EWEA 2012).

At the end of 2010, 200 GW wind energy capacity was installed worldwide with an estimated generation of 410 TWh or 2% of the electricity consumption in the world (BTM 2011). The largest installed wind capacity in 2010 was first seen in China and second in the U.S.A. China doubled its wind nominal capacity in 2009, while installation in 2010 consumed a record of 19 GW. This corresponds to half of the whole wind turbine capacity added in the world that year and made China become the first country in the ranking of globally cumulative installed capacity. In terms of CO_2 emission, Europe's installed wind energy in 2011 generated 204 TWh or 6% of the electricity consumption of EU-27 countries and helped avoid emission of 133 million tonnes of CO_2 per year, equivalent to removing 30% of all cars in the EU off the roads (EWEA 2010).

Wind energy is available as the wind blows, as is commonly said. Since we cannot cover all basic aspects of wind energy here, let us provide some relevant starting points for the readers who may want to learn about these basics beforehand to focus on the issues relevant to wind energy and its climate vulnerability. First, an interactive introduction can be found online at windpower.org, while a solid overview of some of the key facts related to wind energy and its role in supplying electricity worldwide is gathered in a document produced by the European Wind Energy Association: *Wind Energy – The Facts* (EWEA 2009). Then, readers interested in a more detailed overview of these basics, also potentially requiring a sufficient scientific and technical background, are directed toward the manuscripts of Manwell et al. (2011) and Ackermann (2012).

The availability of wind energy at time scales of months to decades is, hence, seen as being mainly linked to trends in average wind speeds. In practice, things are slightly more complicated, since the possibility to optimally use wind energy is also linked to its variability and predictability at shorter time scales, in line with those characterizing our electricity consumption patterns and of those for the operation of the power. In addition, as can already be the case for a country with a very high wind power penetration like Denmark, wind farms may, for some time over the year, produce more energy than needed. Fortunately, Denmark has good transmission connections to its neighboring countries and the resource is normally not wasted at this time. Electricity can difficultly be stored today or be efficiently converted to other forms of energy. Finally, other climate parameters may be of importance, since, e.g., waves and sea ice may affect the accessibility of offshore wind farms, while local temperature fields may affect local thermal winds.

In order to discuss wind energy and its climate-related vulnerability, it is necessary to fully appraise the context and process of generating electricity from the wind. Some of these aspects are introduced and reviewed in the first stage below, by linking the wind resource itself and the electrical power generated from wind turbines or more generally wind farms. The challenges brought by the integration of wind energy into power systems and electricity markets are looked at, in the second stage, in order to fully describe the contextual aspects. Finally, in a third part, the sustainability and climate vulnerability of wind energy are discussed with focus on long-term trends in wind speeds, expected changes in its variability, issues related to icing and its consequences for wind turbine operations, as well as general aspects of extracting energy content from the atmosphere.

3.03.2 The Wind Resource and Related Electrical Power Generation

3.03.2.1 The Global Potential for Wind Energy

A first relevant issue is to figure out how much energy there is around and that could be extracted from the wind. This overall amount of energy is commonly referred to as global potential for wind energy. As an example analysis, Jacobsen (2009) reported that the globally-available wind power over land in locations worldwide with mean wind speeds exceeding 6.9 m/s at 80 m height is estimated to 72 TW (potentially generating 630–700 PWh/year). This resource would represent 5 times the world's total power production and 20 times the world's electric power production. Let us describe a bit more how one ends up with such potential.

In a comprehensive article, Miller et al. (2011) quite schematically break down the available wind resource, with the following reasoning. The Earth receives some 175.000 TW of radiation from the Sun. Of this, about 25% ends up heating the Earth. Since the Earth is round, the incoming radiation is not evenly heating up the surface. The uneven heat distribution leads to atmospheric pressure differences. Then again, only about 2% of that energy is converted into motion (Lorenz 1955), so that the total wind power content in the atmosphere is about 900 TW. About half of this is within the atmospheric boundary layer, which corresponds to the layer of the atmosphere where wind turbines are located. Assuming extraction, only onshore and near-shore (on the global scale) and excluding glaciers, a bit over 25% of the earth's land surface is available for the erection of turbines. Of the resulting 112 TW of power, about 68 TW can be converted to wind power when accounting for the Betz limit (to be discussed below when describing the conversion of wind into electric power). This would finally lead to approximately 596 PWh/year. This number does not exclude sites on grounds of their economic potential, where wind speeds would be too low to successfully place wind turbines. Since there are major uncertainties in this back-of-the-envelope estimate, it should be used as an indication of extractable wind power only. As there exists a number of feedback mechanisms between wide-spread wind power use and the atmospheric system, these mechanisms would require more investigation (which cannot be covered here), before a more realistic estimate can be obtained.

Going further than these simplified calculations, estimations of the global potential for wind energy may be refined by using the methodologies behind the production of wind atlases (see, e.g., windatlas.dk), i.e., with more focus the meteorological phenomena at the Earth's surface. For instance, the fourth assessment report from the International Panel on Climate Change reviewed the available literature and came up with a total technically exploitable potential for wind energy of 50 PWh/year. In the more pertinent Special Report on Renewable Energy Sources and Climate Change Mitigation (Wiser et al. 2011), a table of nine global assessments of global wind energy potential is shown, with different assumptions reaching potentials between 19.4 and 840 PWh/year. The high end is above the quick assessment of the total exploitable kinetic energy content of the atmospheric boundary layer (596 PWh/year), and therefore highly unlikely. For an overview and discussion of recent studies focusing on the global potential for wind energy, the interested readers are referred to Moriarty and Honnery (2011).

Even when using these more advanced approaches looking at relevant meteorological phenomena, these assessments of the global potential for wind energy are based on relatively coarse meteorological models with horizontal resolutions of tens of kilometers. Since terrain features are resolved at a distance of four to seven grid points only (Skamarock 2004), the practical horizontal resolutions of these models are certainly greater than 100 kilometers. Consequently, all the terrain effects that are known to increase wind speed, such as local speed-up effects over hills for instance, are ignored in these large-scale meteorological models. As a highly relevant practical example, Badger et al. (2010) showed that for a complex terrain site, the additional use of a microscale model like WAsP (www.wasp.dk) increases the mean wind power density for the best 50% of the area from 378 to 641 W/m^2. This means that for typical wind power sites, the resource is usually better than indicated by large-scale meteorological models. However, a caveat is that the higher resource is only valid for the best 10–30% of sites in a given area. Once the hill tops have been used for wind farms, the lower lying area is not as good anymore.

Overall, it is to be understood that even though the global potential for wind energy is fairly high, the uncertainty about its actual value, due to various considerations ranging from the impact of meteorological phenomena to the effect of the Earth surface itself, is also significant. Especially since a number of these influential factors are left substantially to chance along with climate evolution.

3.03.2.2 The Energy in the Wind and Its Harvesting through the Power Curve

The generation of energy from wind turbines originates from the weather and can, hence, be linked to some meteorological variables. This is the case for all common types of renewable energies: for hydro power, the energy content in a water reservoir is a function of rain and snow melt, while for solar energy, solar irradiance and cloud cover are some key meteorological variables.

The power output of a single wind turbine is a direct function of the strength of the wind over the rotor swept area. While wind speed is the meteorological variable of most relevance to power generation, air density (being a function of temperature, pressure, and humidity) also influences power output to a certain extent. This is since wind turbines convert the kinetic energy that is present in the wind into mechanical energy, consequently used for operating an electrical generator. Also, the wind over the rotor swept area varies with height, defining the so-called wind profile. The dependence on height is then linked to surface roughness, being different if offshore or onshore, and also a function of vegetation in the latter case. This dependence is also linked with atmospheric stability, roughly given by the vertical temperature gradient, accounting for the water surface temperature in the offshore case.

The process of the conversion of wind to electric power for a single turbine is described by the wind turbine power curve. Power curves roughly have the same shape no matter the manufacturer or turbine type. In mathematical terms, the underlying relationship between wind speed and power generation is explained by the cubic power law: the power available in the free flowing stream of wind is a cubic function of the wind speed. In parallel, owing to a number of factors like the Betz limit (or the more general limit derived by Okulov and Sørensen (2008)), the generator, and gearbox efficiencies as well as other losses, it is only possible to extract a certain percentage of the original power available in the wind.

In practice, a power curve has the characteristic form of example one depicted in Figure 1. The power production is

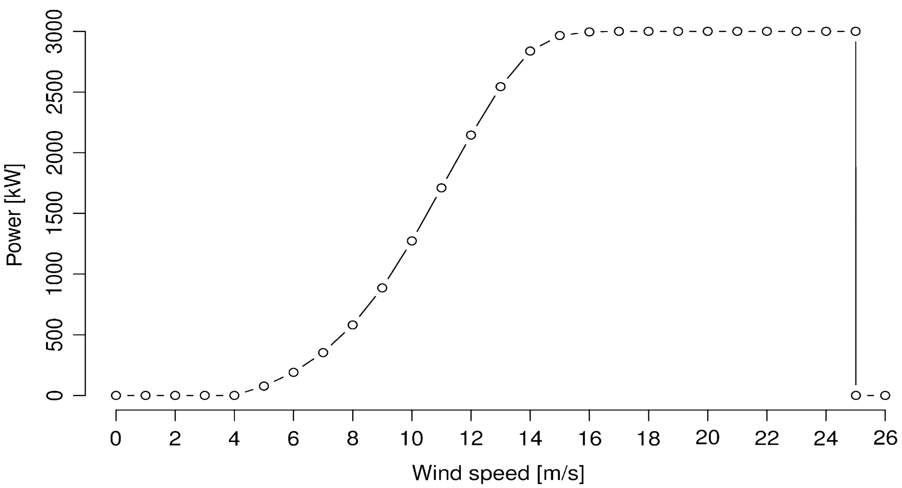

Figure 1 Example manufacturer power curve, for the Vestas V90 wind turbine with a nominal capacity of 3 MW (for an air density of 1.225 kg/m^3). Even though today, the nominal capacity of a wind turbine may be up to 5 MW, the characteristic shape of the power is still pretty much the same.

null below the cut-in wind speed, then sharply augments between the cut-in and rated wind speeds. At rated speed, it reaches nominal power, which is the power for which a turbine has been designed to operate. The nominal power serves as a reference value for denoting the capacity of a turbine and computing expected energy yields depending on site characteristics. The power production is close to being constant between the rated and cut-off wind speeds. At cut-off speed, the turbine stops for security reasons. This example of a power curve is for a fairly old wind turbine model from the 1990s. Various technological improvements have permitted lower cut-in and rated wind speed, while augmenting the cut-off speed.

It should be noted that these aspects of the conversion of the energy in the wind into electric power are of particular importance, since technological advances may indeed allow mitigating the potential effects of climate changes on our ability to harvest wind energy. For instance the changes in cut-in, rated and cut-off speeds will support energy extraction even if (very) low and high wind speeds were to become more frequent in the coming decades. Inversely, there will always be a steep part in such a power curve, which will amplify the magnitude of the fluctuations in the wind. The potential consequences of fluctuations of high magnitude will be discussed further below.

3.03.2.3 Spatial and Temporal Variability of the Wind Resource

Coarsely simplifying the meteorological aspects involved, winds originate from the movement of air masses from high to low pressure systems: the larger the difference in pressure, the stronger the resulting winds. This simple picture concerns the so-called geostrophic wind approximation for altitudes of, say, 1–2 km above ground level. Geostrophic winds can be seen as the free flows not affected by the Earth surface effects. Closer to the ground in the boundary layer, the winds' behavior becomes more complex due to natural obstacles, friction effects, the nature of the surface itself, temperature gradients, etc. As mentioned above, this potentially has the effect of increasing the density of wind power per unit surface area.

As a consequence, wind speed exhibits fluctuations over a wide range of frequencies. At the lowest end of the frequency range, variations in the order of days and over large geographical areas are induced by the movement of synoptic weather patterns, in more common terms by general changes in weather situations. In parallel, the fluctuations referred to as diurnal and semidiurnal cycles exist at a period of 12 and 24 h and for more localized areas, for instance at a coastline. They originate from thermal exchanges between the surface (land or sea) and the atmosphere, being weaker or stronger depending upon local climate, and also varying with seasons. For higher frequencies in the order of minutes to hours, more local effects potentially including the presence of cumulus clouds, convective cells, precipitation, or waves (for offshore sites) are the drivers for wind speed variations. Finally at higher frequencies (seconds to a few minutes, very small spatial scales), turbulence effects dominate. They are of less importance for the discussion here.

It was previously mentioned, that the lowest end of the frequency range corresponded to temporal scales in the order of days. This would be assuming that there is no variation at lower spatial and temporal scales, while it is actually the case. The effect of this interannual variability is, for instance, extensively treated by Pryor et al. (2006). As an illustrative example, the evolution of the yearly averaged wind speed (at 10 m above ground level) at the Schiphol airport near Amsterdam is shown in **Figure 2**, for the 55 years between 1950 and 2005. The average wind speed over that period is of 5.3 m/s, while the

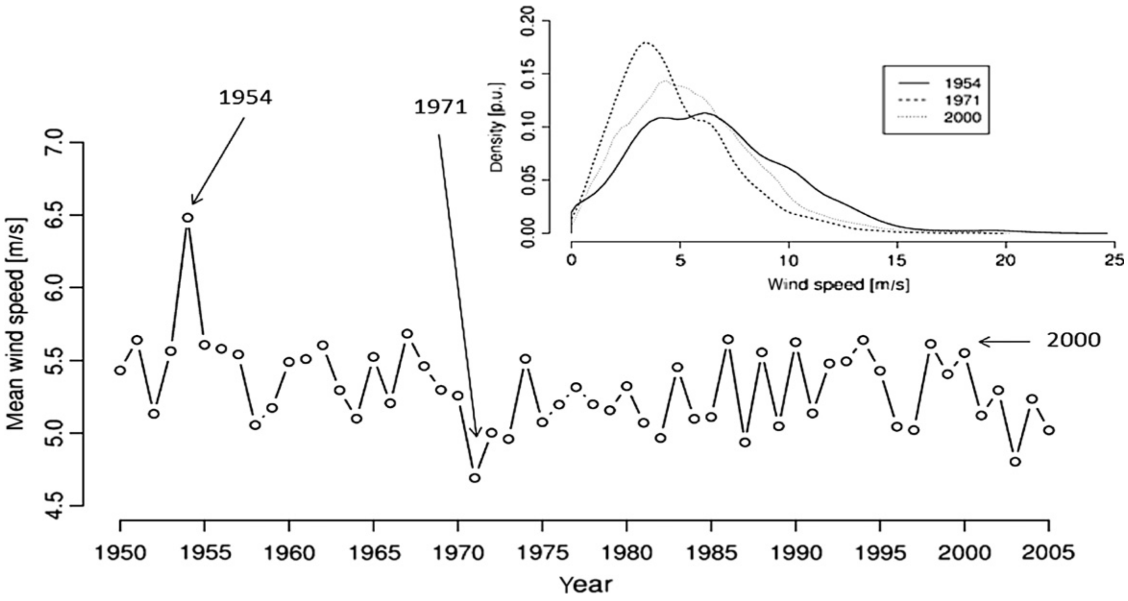

Figure 2 Evolution of the yearly mean wind speed at the Schiphol airport near Amsterdam, at 10 m above ground level. Wind measurements were taken from the KNMI-Hydra dataset (KNMI is the Royal Netherlands Meteorological Institute, which is duly acknowledged for making this dataset available). The average wind speed over that period is 5.3 m/s, while the variations from one year to the next are in the order of 0.5 m/s.

variations from one year to the next are in the order of 0.5 m/s. These variations may not appear that important (roughly only 10%). In practice, however, they will have a large impact on the distributions of wind speeds over the year (also shown in **Figure 2** for three example years), which are then amplified through the steep part of the power curve of wind turbines. Resulting changes in yearly energy throughput may be much greater due to the cubic effect of wind speed on power. In their discussion on the vulnerability of wind energy to climate, Schaeffer et al. (2012) insist on the fact that looking at trends in mean wind speed is clearly not sufficient, since a complete knowledge of wind speed distributions (and also of wind speed at various temporal and spatial frequencies) is necessary for appraising impacts on wind power generation.

To better explain and understand these very low frequency variations in wind speeds, Brayshaw et al. (2011) recently argued that they can be partly explained and predicted by large-scale climate patterns like the North Atlantic Oscillation (commonly abbreviated NAO). More generally, the linkage between wind characteristics and these large-scale climate patterns may be quite complicated, as indicated by a parallel study of Wang et al. (2011). Indeed, they uncovered that even though storminess (and hence wind speeds that would be close to wind turbine cut-offs) could somehow be related to the NAO, their relationship may be highly varying temporally and geographically. Overall, the crucial aspect to be remembered here is that characteristics of the wind relevant to power generation (e.g., mean wind speed, fluctuations, high winds) may be directly linked to some of the longer-term climate signals. This will be the particular focus of one of the further sections of this chapter.

3.03.2.4 Onshore and Offshore Specifics (Resource)

Generally, two major properties of the surface play a role for wind energy: the roughness of the landscape and the orography (i.e., terrain height variations). The wind speed is zero at ground level. With increasing altitude, it reaches the speeds given by the geostrophic winds above the boundary layer. Within the lowest layer, 80–150 m, the wind speed logarithmically rises with height, with a scaling parameter called the roughness. In high-roughness terrain, like cities or forests, the wind speed only slowly increases with height, while in low roughness terrain like grassland, sand, or sea, the wind speed quickly increases with height. For a good overview of wind power meteorology, see either Petersen et al. (1998a,b) or the WAsP help file (see www.wasp.dk). In the high-roughness areas, a few extra meters of tower for the wind turbine can pay off due to the higher energy in the wind higher up. While on grassland or offshore, the towers just have to keep the rotor high enough above ground as to not have too much wind shear (i.e., different speed) between the top and bottom of the rotor. Wind shear is a design parameter for the wind turbine and should not exceed a certain amount; otherwise, the lifetime of the turbine is going to suffer. Another feature of high roughness is the added turbulence, since small eddies are created at the terrain features.

While a different roughness in a wind resource calculation can change the result by rarely more than 20%, changes in orography or placement of the turbines on a hill can change the resource up to 70% due to the speed-up effect. On the top of a mountain the wind streamlines are compressed, and the Bernoulli effect keeping the mass flow constant increases the wind speed on top of the hill. However, the effect of mountains and hills is not limited to compression of the streamlines. At higher slopes, the wind can detach from the surface and start to come into large eddies behind the hill, in so-called recirculation zones. Those are very difficult to properly predict, and also with great computational effort, one cannot be sure to find the right result for the wind flow. However, as previously mentioned, in those areas, the wind resource is significantly enhanced in comparison to a coarser assessment, so in many cases, this is where wind power is built.

The situation is different offshore. For obvious reasons, orography does not play a role here, and the roughness is very low. This leads to a very low turbulence, high wind speed gradients with altitude, and generally higher wind energy. The lower turbulence also means lower variability, as the wind is generally not influenced by terrain variations for long fetches of ocean. In some cases, however, some special offshore weather types, such as open cellular convection, can increase the variability of offshore winds (Vincent 2011).

Wind turbines are usually arranged in wind farms, also called wind power plants due to the recent rise in size and possibilities to support the power system in critical times. Within those wind power plants, an optimization has to be done between the close spacing of turbines due to land availability, cabling cost or other needs, and the decreased wind resource due to wakes between the turbines. The wind turbine works by extracting kinetic energy from the wind, thereby slowing it down. A downstream turbine will therefore see less wind than one standing in the free stream. Onshore, this is taken care of by sufficient distance between the turbines, for example, five to seven rotor diameters. However, offshore in the reduced turbulence, the distances would have to be larger, as the wake structure can keep intact for a longer time. Satellite pictures have revealed that the wake (i.e., the area with reduced wind speed) behind the Danish offshore wind farm of Horns Rev can reach tens of kilometers (Christiansen 2007).

3.03.3 The Technological and Policy-Related Challenges for Wind Energy Integration

The global potential for wind energy may be seen as highly significant overall, while this available energy is well harvested through the conversion of wind to electric power. In parallel, our current understanding of space-time effects and onshore/offshore specifics was shown to be fairly good. It appears, however, that it is not only this core aspect of the resource that is of importance when considering the large-scale deployment of wind power and its potential climate vulnerability. Indeed, the context of the technological and policy-related challenges clearly contributes to the final use we make of the available wind energy. To push it to the extreme, some say (Inhaber (2011) for instance) that wind power cannot provide the benefits anticipated in terms of reductions of overall energy costs and CO_2 emissions. The reasons for such decrease in potential benefits from using wind energy mainly originate from the difficulty to integrate wind power generation into the existing power systems and electricity markets, especially when wind power penetration reaches substantial levels (say, more than 20–30% of the demand met over the year).

Some of the concepts of importance related to power systems operations and electricity markets are reviewed in the following, starting with the costs of wind energy and the policy framework. Then, we build on the question of the variability of the wind energy resource that was previously discussed by then looking at its predictability. Finally, we revisit the onshore and offshore specifics with focus on these technological and policy-related challenges.

3.03.3.1 The Cost of Wind Power

Even with a great resource, wind energy generation will only be used if eventually being an economically attractive form of energy. This is the reason why the economics of wind energy (for wind turbines connected to the power grid, that is, the vast bulk of installed wind turbines) is rapidly covered here. Some of the main parameters governing wind power economics include investment costs (also for foundation, grid-connection, etc.), operation and maintenance costs, turbine lifetime and discount rate, and finally the wind resource itself as discussed in the previous section. Of these, the most important parameters are the turbines' electricity production and their investment costs, while the parameters most affected by a potential climate evolution, are again the electricity generation from the turbines as well as the operations and maintenance costs.

As electricity production is highly dependent upon wind conditions, choosing the right turbine site is critical to achieving economic viability of the project. A major trend in recent years relates to the steady increase in the size of the turbines, being both larger and taller. Turbines are also more efficient in producing electricity, also making wind energy less vulnerable to low and very high wind conditions.

Some of the important costs related to wind energy and how they may be affected by climate-related aspects are viewed below. This potential impact of climate will most likely translate to increased costs of installing and operating wind farms.

3.03.3.1.1 Capital Costs

Capital costs of wind energy projects onshore are dominated by the price of the wind turbine itself (ex. works, i.e., the turbine as provided by the manufacturer and transported to the site). To give a rapid overview, Table 1 shows the cost structure for a medium sized turbine (850–1500 kW) sited on land and based on data selection from UK, Spain, Germany, and Denmark over 2001/2002. The turbine's share of total cost is typically a little less than 80%, but as shown in Table 1 considerable variations exist ranging from 74–82%. The single most important additional component is the cost of grid connection, which in some cases can account for almost half of balance-of-plant costs, followed by foundation, and cost of the electrical installation. Cost components such as consultancy and land normally account for only minor shares of balance-of-plant costs.

These costs may obviously differ if wind turbines are to be located in a certain country or another, though these variations are somewhat limited (Lemming et al. 2008). It appears overall, that these costs cannot be greatly impacted by climate-related aspects, since only the cost of land and road construction could be directly affected.

Table 1 Cost structure for a typically medium sized wind turbine (850–1500 kW), based on a limited data selection from Germany, Denmark, Spain, and UK for 2001/02. The cost structure tends to be fairly stable over time.

	Share of total cost (%)	*Typical share of other costs (%)*
Turbine (ex. works)	74–82	–
Foundation	1–6	20–25
Electric installation	1–9	10–15
Grid-connection	2–9	35–45
Consultancy	1–3	5–10
Land	1–3	5–10
Financial costs	1–5	5–10
Road construction	1–5	5–10

3.03.3.1.2 Operation and Maintenance Costs of Wind-Generated Power

Operation and maintenance (O&M) costs constitute a sizeable share of the total annual costs for a wind turbine. For a new turbine, these costs might easily reach an average share over the lifetime of the turbine of approximately 20–25% of total levelized cost per kWh produced. Therefore, O&M costs are attracting increasing attention, while manufacturers are attempting to lower these costs by developing new turbine designs requiring fewer regular service visits and less out-time of the turbines (higher availability). O&M costs are related to a limited number of cost components, which include regular maintenance (scheduled), repair (unscheduled), spare parts, insurance, and administration.

Based on existing experience from Germany, Spain, UK, and Denmark, O&M costs are, in general, estimated to be at a level of approximately 1.2–1.5 c€/kWh of produced wind power seen over the total lifetime of the turbines. Data from Spain indicate that a little less than 60% of this amount strictly goes to O&M of the turbine and the installations, the remaining 40% being almost equally split into insurance, rent of land (considered as part of O&M costs in Spain), and overhead.

Even though these O&M costs may appear quite limited today, these are the costs that may be the most impacted by climate for two reasons. The first is that turbines are subject to extreme winds and gusts; if they become more frequent, the number of failures and necessary unscheduled repairs would necessarily increase. The second is that accessibility to the wind farms would be reduced if more extreme weather conditions occurred, especially in the offshore case (high winds, waves, or sea ice).

3.03.3.1.3 The Cost of Energy Generated by Wind Power

The total cost per produced kWh (unit cost) is calculated by discounting and leveling investment and O&M costs over the lifetime of the turbine, divided by the annual electricity production. The unit cost of generation is thus calculated as an average cost over the turbine's lifetime. In reality, actual costs will be lower than the calculated average at the beginning of the turbine's life, due to low O&M costs, and will increase over the period of turbine use.

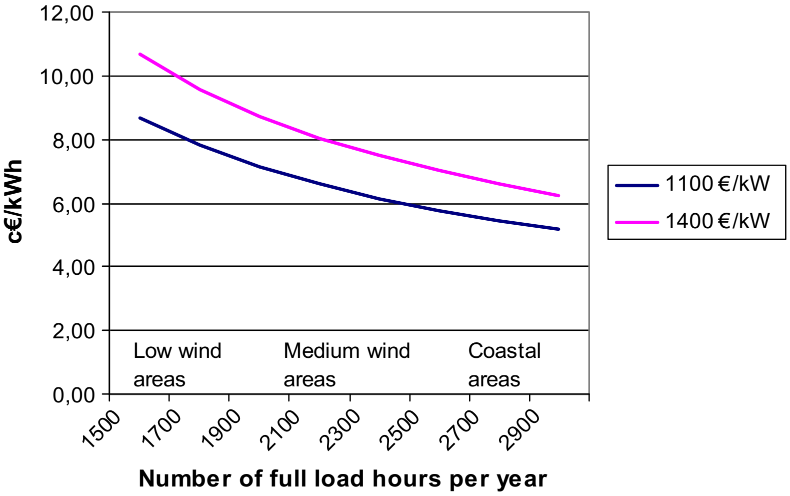

Figure 3 Calculated costs per kWh wind generated power as a function of the wind regime at the chosen site and two specific investment levels (number of full load hours).

The turbine's production of power is the single most important factor for the cost per generated unit of power. If a turbine is or is not sited at a good wind location, may totally determine if the turbine is profitable or runs with a loss. An example of the cost of wind produced energy is shown below based on the following assumptions:

- The calculations are performed for a land based medium sized turbine that is 850–1500 kW in size (a small turbine today).
- Investment costs equal 1100–1400 €/kW with an average of 1175 €/kW.
- Operation and maintenance costs are 1.45 c€/kWh in average over the lifetime of the turbine.
- The lifetime is set to 20 years.
- The discount rate is 7.5%.
- The economic analyses are carried out as socio-economic ones. No taxes, depreciation, risk premium, etc., are taken into account.

The calculated costs per kWh wind generated power as a function of the wind regime at the chosen sites are shown in Figure 3 below (In the figure, the number of full load hours is used to represent the wind regime. Full load hours are calculated as the turbine's average annual production divided by its rated power. The higher the number of full load hours, the higher the wind turbine's production at the chosen site). As shown, the cost ranges from approximately 7–10 c€/kWh at sites with low average wind speeds to approximately 5–6.5 c€/kWh at good coastal positions, with an average of approximately 7 c€/kWh at a medium wind site.

Approximately 75–80% of total power production costs for a wind turbine are related to capital costs, that is, costs for the turbine itself, foundation, electrical equipment, and grid-connection, etc. Thus, a wind turbine is so called capital intensive compared with conventional fossil fuel fired technologies as a natural gas power plant, where as much as 40–60% of total costs are related to fuel and operation and maintenance costs.

3.03.3.2 Policy Framework

Looking at the countries in, e.g., Europe that have installed significant amounts of wind energy in their electricity system, it is apparent that both the wind resource and the state of the technology are not in themselves the only determining factor. The growth of the wind energy sector in many countries is strongly affected by and responsive to the political frameworks, as well as a wide range of government policies. During the past two decades, a significant number of developed countries and, more recently, a growing number of developing nations have laid out renewable energy policy frameworks that have played a major role in the expansion of the wind energy market. These efforts have been motivated by the environmental benefits, climate change, security of supply, and economic development impacts of wind energy deployment, as well as the potential for reducing the cost of wind energy over time.

An early significant effort to deploy wind energy at a commercial scale occurred in California, with a combination of aggressive state and federal tax incentives spurring rapid growth in the 1980s. Nearly 2000 MW was installed until the California Public Utilities Commission suspended the market in 1985 (Bird et al. 2005). In the 1990s, wind energy deployment moved to Europe, with feed-in tariff policies initially established in Denmark and Germany, and later expanding to Spain and a number of other countries. A European study compared the support mechanisms that have been used and concluded that the most effective (ability to deliver an increase in renewable energy share in electricity delivered to consumers) and efficient (total support paid versus generation cost) support mechanism for onshore wind energy in Europe has been the feed-in tariff. In the U.S.A., the support mechanisms that have been used have been compared in a similar study (Bird et al. 2005) and the conclusion is that for the U.S.A., the renewable portfolio standards have shown to be the most effective support mechanism for wind energy.

Climate clearly has an impact on the resource itself. Our ability to harvest it and its potential cost may be counterbalanced by more proactive policies supporting further development and use of wind energy.

3.03.3.3 Power Systems Operation, Electricity Markets, and the Predictability Challenge

The management of an electric power grid is a difficult task, even when only the demand is variable and all power plant output can be scheduled, since production and demand should be strictly matched at all times. As previously explained, wind energy generation cannot be scheduled while being highly variable. This has the consequence of making the power grid even more difficult to manage, while potentially increasing the various costs involved. Another consequence is that at large levels of wind power penetration, this constant-matching constraint may lead to spilling of wind energy when very large quantities of wind energy are produced when not needed.

While the final operation of the power grid is that task of the grid operator, optimal schedules and dispatch are increasingly determined based on electricity markets, where the various demand and production offers are accordingly gathered and matched. A core characteristic of these electricity markets is that all offers should be submitted a certain time in advance, from a few minutes to more than a day.

Consequently, in view of the time scales relevant for the operation of power systems and electricity markets and given the variability of wind energy generation, it is necessary to predict what wind power production may be in the near future. Forecasting of wind power generation is currently seen as a challenge, at least at levels of accuracy required by the users of such forecasts. It has consequently attracted the attention of a large number of researchers and practitioners, spanning a wide range of potential paths for forecast improvements.

These time scales of interest range between a few minutes to several days ahead. The shorter lead times correspond to the needs of the grid operator (often referred to as Independent System Operator, ISO, or Transmission System Operator, TSO) in order to optimally operate reserves for the continuous balance of the power system. They also serve as input to wind farm controllers (most importantly for large wind farms situated offshore). These short-lead times are also relevant for market participation in countries like the Australia, New Zealand, and U.S.A. In contrast, in the European context of power systems operations and market participation, the lead time of interest are up to two days ahead since commitment and dispatch are based on a day-ahead market.

In an operational context, prediction systems use past and real-time power and meteorological observations as input, as well as current weather forecasts provided by National weather offices or alternatively by commercial forecast providers. The latter permit one to capture the trend in the evolution of weather systems, and these may affect relevant meteorological variables at the level of the wind farm (or portfolio) of interest. In parallel, the observations permit one to fully appraise the current situation at the level of the wind farm and to take advantage of the inertia in the evolution of weather systems to better predict its evolution in the short term.

A potential issue with these wind power forecasts relates to their level of accuracy. Their quality may indeed be highly variable and characterized by a wide range of factors. The lead time of the forecast is obviously one key factor, as one naturally expects forecasts to be less accurate as the lead time gets further in the future due to the inherently chaotic behavior of the atmosphere. Also, the quality of the forecast highly depends upon the local wind climate and local terrain where wind farms are located; it is easier to predict wind power generation in the North of Denmark than on the steep hills of the South Pyrenees in Spain. Finally, forecast accuracy is also highly dependant upon the forecast provider and the method he uses.

The lack of predictability of future wind power generation is commonly seen as a threat to the reliable and economic integration of this renewable energy in current power systems. Various studies have shown, however, that the progress in predicting such power output has been tremendous over the last decade. As a representative example, Ernst et al. (2007) showed that the level of root mean square error for wind power predictions over all of Germany decreased by 1/3 between 2001 and 2006. More improvements are expected in the near future owing to the increased commitment of the meteorological community for upgrading the current forecast systems for relevant meteorological variables.

A reason why we mention the challenge of predictability is that we are not sure of the predictability of relevant meteorological variables into the future. Some very preliminary works have actually been looking at whether or not it is possible to predict wind power generation for the next season, based on some seasonal forecasts of climate indicators (Brayshaw et al. 2011). Direct approaches based on statistical considerations may already permit one to predict the average energy generation for the coming month (García-Bustamante et al. 2009).

3.03.3.4 Onshore and Offshore Specifics (Technology and Integration)

Compared to land-based turbines, the cost structure of offshore wind farms are mainly related to the three following issues. First, foundations are considerably more costly for offshore turbines. The costs depend on both the sea depth and the chosen principle of construction. For a conventional turbine sited on land, the share of the total cost for the foundation is normally approximately four to six percent. In contrast, for the first two large offshore projects in the world, Horns and Nysted in Denmark, the foundations accounted for 21% of the total investment. Second, the cost of the grid connection, i.e., the transformer station and the transmission cable to land, may be much higher for offshore wind farms. The connections between the turbines and to the centrally located transformer station are buried in the sea bed and generate additional costs compared with on-land sites. Again, for these two large offshore projects at Horns Rev and Nysted, the average cost for the transformer station and main transmission cable represents 16%, while the so-called array cables connecting the turbines with the transformer station account for 5% of the total project investment. Finally as a third point, access to an offshore wind farm is often by boat or in some cases by helicopter. This is considerably more difficult and expensive than for a land-based turbine and the cost of operation and maintenance (O&M, the most influenced by climate parameters) is typically 30–40% higher than for land-based wind farms. As an illustrative example, Nielsen et al. (2010) analyzed the main differences between Danish land-based and offshore projects, also including a projection until 2050. Overall, it was concluded that the cost of electricity today is approximately 40% higher from an offshore wind farm than from a land-based wind farm. This difference is expected to lower to 25% by 2050.

In parallel, regarding the integration of the electricity generated, a specificity of offshore wind power is that offshore wind farms concentrate very large capacities at a single location or over a fairly small area. It is common today to talk of future offshore wind farms with nominal capacities in GWs. Onshore, the same level of installed capacity is usually spread over an area of significant size, which yields a smoothing of power fluctuations (Giebel 2007). Since this smoothing is hardly present offshore, the magnitude of power fluctuations may reach very significant levels and require more flexible generation units connected to the grid in order to mitigate these large fluctuations. A discussion on these aspects is available in Sørensen et al. (2009). This finally translates to additional costs for the management of the power system to be put into perspective with the larger quantities of wind energy that can be harvested offshore.

3.03.4 Climate and Wind Energy

Some of the crucial climate parameters for wind energy were discussed in Section 3.10.1 Introduction. By far, the most important of these parameters is the wind in the lowest part of the atmosphere. Local winds depend on the surface characteristics: terrain, type of surface, and nearby obstacles and are always superimposed upon the larger scale wind systems. When larger scale winds are light, local winds, e.g., sea breezes may dominate the wind pattern at the location of a wind turbine. Thus, changes in global, regional, or local temperature fields in local vegetation and in other factors will affect the wind climate. Note, however, that other climate parameters may also be of importance, as for instance icing has a noticeable impact on wind energy production. Overall, emphasis is placed here on some of the ways wind energy technology and the electricity production may be affected by climate, owing to changes in (i) the wind resource, (ii) extreme wind speeds (50-year wind), (iii) occurrence of atmospheric icing, and (iv) occurrence of sea ice (especially relevant for offshore applications).

A network of more than 60 researchers from Nordic countries worked between 2003 and 2010 on assessing the impact of climate on all renewable energy sources in the five Nordic countries. The work was structured into two large projects: Climate and Energy (2003–06) and Climate and Energy Systems (2007–10) http://en.vedur.is/ces, financially supported by the Nordic Council of Ministers and the Nordic energy industry. All renewable energy sources of importance for electricity generation were studied, i.e., hydro power, wind, solar, and biomass. The basis for quantifying the climate impact was a comprehensive study of a large number of scenarios generated by global and regional climate models. The main results from the two projects with regard to wind energy were reported in Clausen et al. (2007) and Clausen et al. (2012), while substantially inspiring the discussion in the present section. A top-down approach was followed there, the conclusions of which may be affected by the limited predictability of relevant climate variables at these time scales at a regional level.

3.03.4.1 Wind Resource

Wind speed in relation with climate has attracted increasing attention over the last years, especially in relation with the issue of generating wind energy. Focusing on wind speeds is quite new – most efforts were originally focused on the temperature variable.

Certain studies mention a global trend of increasing values in wind speed, like the recent one of Young et al. (2011) focusing on oceanic wind speeds based on a 23-year database of calibrated and validated satellite altimeter measurements, or that of Troccoli et al. (2012) concentrating on the Australian case. In contrast, other works observe that terrestrial wind speeds have slowed down over the last decades (McVicar and Roderick 2010). Overall, review articles analyzing these various studies conclude on a cautious note, such that it may actually be difficult to formulate solid conclusions on future average wind speeds over the coming decades (Pryor and Barthelmie 2010), especially if considering the question of wind speed at various heights relevant for wind energy generation. This is owing to the complex mechanisms involved in the evolution of climate variables, not only affecting average wind speeds close to the surface but also parameters that may affect wind profiles (i.e., the way that wind speed evolve depending upon height). For instance in response to the work of McVicar and Roderick (2010) and Vautard et al. (2010) explained that the stilling in observed wind speeds could be partly explained by changes in surface roughness (for 10–25%), linked with biomass and land-use change in Eurasia. In parallel, changes in atmospheric circulation, as captured from the ERA-Interim reanalysis data, could explain between 10 and 50% of this observed decrease in wind speeds. **Figure 4** gives an illustration of the main results from that study, showing the trends in wind speeds observed at meteorological stations worldwide and from the ECMWF ERA-Interim reanalysis. For more information on this reanalysis, which is widely used as input to climate studies, the reader is referred to Dee et al. (2011).

3.03.4.2 Extreme and Strong Winds

The extreme wind U_{50} is the 10-min average wind speed with a return period of 50 years and is an important design parameter for wind turbines, while strong winds are more important for the operation and maintenance of especially offshore wind farms. Most offshore wind farms are accessed by boat. Before a visit to an offshore wind farm, the operation and maintenance planner looks for so-called weather windows where the wind and wave spectra allows access to the wind farm twice: first to place the maintenance crew and their tools at the wind turbines and second to pick them up after the work is finished. The number of days per year where the wind farm can be accessed is used during the planning period where the developer will compare potential wind farm sites and different means to access the wind farm; second, in the daily planning of maintenance, strong winds

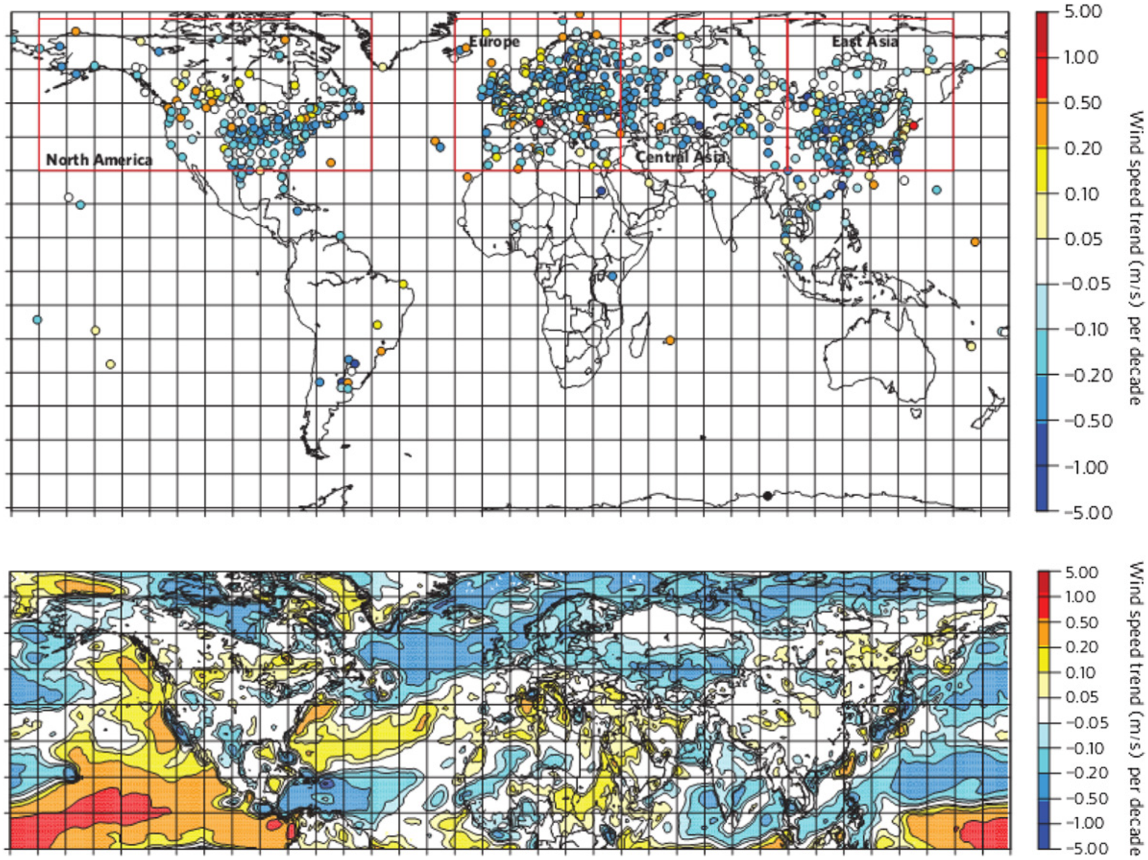

Figure 4 Observed and reanalysis surface wind speed trends (taken from Vautard et al. 2010). Top: linear trends in the observed wind speeds at selected meteorological stations (822 worldwide) in m/s per decade, over the period 1979–2008. Bottom: linear trends from the ECMWF ERA-interim reanalyses, calculated using mean daily 10 m wind speed values over the period 1989–2009. Reproduced from Vautard, R., J. Cattiaux, P. Yiou, J.-N. Thépaut, and P. Ciais, 2010: Northern hemisphere atmospheric stilling partly attributed to an increase in surface roughness. *Nat. Geosci.*, **3,** 756–761.

influence decision-making concerning ship travel to the wind farm. In this respect, strong winds are important as they occur much more frequently than extreme winds (e.g., wind speeds >17 m/s occur 3–4 days per year at 10 m height in the Fehmern Belt between Denmark and Germany).

Studies about the effect of climate variability on strong and extreme winds are rare while mainly following a top-down approach. They were recently reviewed by Pryor and Barthelmie (2010). As shown in Figure 2, changes in yearly average wind speeds translate to potentially substantially different distributions of wind speeds over the year. Intuitively, higher average wind speeds yield more frequent strong wind speeds and larger probabilities of observing extreme wind speeds. Therefore, even if higher mean wind speeds may be seen as beneficial, allowing more energy to be produced from the wind over the year, this may not be realized in practice due to the potentially negative effects of strong and extreme winds, for instance, those related to cut-off events, turbines failures, and access problems for offshore wind farms.

In contrast to this top-down approach based on climate models permitting projections to be made regarding future extreme wind speeds, a bottom-up strategy evaluates which increase in extreme speeds (magnitude and frequency) may be tolerated by current technology while not leading to additional challenges in terms of offshore wind farm accessibility.

3.03.4.3 Icing

With the development of new wind projects in the Northern part of Scandinavia, Canada, Austria, and Switzerland, a new market segment for wind power has emerged: wind power in a cold climate. The market conditions here can be divided in two sub-groups: areas with occurrence of low temperatures and areas where icing will occur. The main effect of icing is decreased aerodynamic performance and potentially excess loads triggered by unevenly distributed ice on the blades. Both lead to a loss in energy production and affect the economics of wind turbines. There might also be health and safety effects associated with operation of wind turbines in areas with icing due to a risk of ice throw (for a reference work on that topic see Biswas et al. (2012)). Sites prone to atmospheric icing are typically located at northern latitudes or at high altitudes, such as mountain ridges that provide favorable wind conditions. Operation of wind turbines in dry areas with low ambient temperatures (below −20 °C) and a low risk of icing, is often a matter of selection of the right steel quality for the wind turbine, installing (e.g., heating in the gearbox) the hydraulic system, and in other critical components in order to facilitate cold start.

Moisture is also an important factor, since increased moisture facilitates icing. Hence, potential evolutions of average moisture levels in the coming decades may affect wind energy.

For instance, even with the projected increasing winter temperatures of more than 2 °C in northern Scandinavia (Kjellström et al. 2012) leading to a trend with fewer icing days, the parallel trend of increased wintertime precipitation and cloud cover (Clausen et al. 2007) may well lead to more frequent icing overall. On the other hand, it is possible that during a transient change these combined weather conditions could undergo a nonlinear change so that the conditions throughout the century may not just be simple scaling or interpolation between present and end-of-century conditions. A more in-depth analysis of freezing point crossover under humid conditions is necessary to provide reliable information about whether these competing mechanisms will result in a temporary increase or decrease of icing conditions as temperatures are on the rise. Note that technological developments will most certainly help making wind turbines less vulnerable to icing.

3.03.4.4 Sea Ice

Let us consider the example of the Baltic Sea, where a number of offshore wind farms are planned, which annually freezes nowadays. The maximum annual ice extent occurs between January and March, when ice covers 52 000–420 000 km^2 and on the average 218 000 km^2. At the latitude of Stockholm, the ice probability is 50%. The ice season lasts from weeks in the south to seven months in the north. The thickness of the ice varies between 50–70 cm during normal winters and 80–110 cm during colder winters. In the coastal areas of the Gulf of Bothnia South and the Gulf of Finland, icing periods last on average for 100–150 days. In the south of Stockholm, the icing period is on average less than 60 days. In the sea areas around Denmark and the West/South coast of Sweden, the icing period is less than 30 days on average.

For wind turbine foundations, the most critical issue is the thickness of drifting sea ice. In coastal regions, limited ice action is exerted against the foundations, as the ice becomes anchored on the shoreline, rocks, shallows, and islands. In early winter ice movements are by thin ice only, while during late spring the ice becomes soft and deteriorated and movements by thick ice is seen. In the northern part of the Baltic Sea, drifting ice can be 0.8 m thick with significant piling of ice. During winter, loads on structures are from thermal ice expansion only. After a storm, ice flows that have broken off can move about, causing loading on structures. The larger the solid ice field, the larger the loads. The greatest loads are usually experienced in springtime, when ice starts moving and piling. In the northern part of the Baltic Sea, the pile up against the tower and foundation can reach a height of 10 m and may damage tower structures.

In terms of climate vulnerability, even though sea ice is certainly problematic for offshore turbines foundations as well as for operations and maintenance of offshore wind farms, climate is assumed to not affect wind energy owing to increased sea ice in the coming decades.

3.03.5 Conclusions

The energy generation from wind turbines is highly sensitive to a number of climate parameters, either directly (wind speed at least) or indirectly (wave, sea ice, etc.). Making projections regarding the climate vulnerability of wind energy is a difficult task. This is because these parameters have attracted less attention from the climate research community than temperature, which was seen as the lead variable when studying climate change. Their potential evolution with a drift in existing climate is then less well understood.

Various studies have looked at trends in wind speeds either globally or at the level of specific countries, with contrasting results and that was potentially inconclusive overall. What comes out of these studies is that instead of only focusing on mean wind speeds and at a particular height (say, 10 m above ground level), it is of crucial importance to appraise the evolution of the complete distributions of wind speeds, not only the mean and at various heights, hence, fully describing the potential wind conditions and wind profiles that the turbines may experience.

In parallel to the wind itself, waves, icing, and sea ice are identified as the main parameters that may indirectly affect wind energy. Icing is relevant to both onshore and offshore cases, while obviously sea ice and waves are only relevant for the latter case. It is difficult to foresee evolutions in wave characteristics – the reason why this was not extensively treated here. Winds and waves are directly related offshore and should be jointly examined. Regarding icing and sea ice, a climate evolution with increasing average regional and local temperatures might smoothly dampen their undesirable effects on wind energy production.

Globally, the climate vulnerability of wind energy is to be put into perspective with the technological and policy-related framework. The technology of wind turbines is evolving and making them less sensitive to very low and very high winds. Technological changes and cycles of decommissioning and decommissioning of wind turbines are faster than climate evolution, allowing for an adaptation of our approach to optimally harvesting energy from the wind. Also, changes in the ways energy mix or the way energy is transported, distributed, and consumed, may help mitigate the effect of enhanced variability and lack of predictability of wind conditions. It is somehow our role to adapt to the specifics of using this form of energy production and to its potential change in characteristics over the coming decades and centuries.

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3.04 Renewable Energy Resources – Ocean Energy: Wind–Wave–Tidal–Sea Currents

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Glossary

AOGCMs Atmosphere–Ocean General Circulation Models.

IEA International Energy Authority.

kWh is a kilowatt hour which is equivalent to 3.6 MJ (i.e., one million (10^6) joules) of energy.

RCMs Regional Climate Models.

SRES Special Report on Emission Scenarios. The SRES scenarios were constructed to characterize possible future emissions of greenhouse gases and aerosol precursor emissions. Examples of these scenarios as used herein are A2, A1B, B1, which are ordered in descending order in terms of the amount of climate forcing (A2 being the highest and B1 the lowest).

Storm tracks indicate preferred regions of extra-tropical cyclone activity.

Technical potential resource accounts for geographical constraints to harnessing the resource and losses in the energy conversion.

Theoretical potential resource is an estimate of the total energy in the fluid.

3.04.1 Introduction and Objectives of This Chapter

According to the International Energy Authority (IEA) global energy use is projected to increase by 1.5% per annum between 2007 and 2030 (International Energy Agency 2011). This projected increase in demand coupled with concerns regarding the current reliance on fossil-fuels and the associated geopolitical and environmental concerns has led to increased interest in harnessing renewable energy sources. Again according to scenarios developed by the IEA, use of non-hydro renewable energy technologies (including wind, solar, tidal, wave, and bio-energy) is likely to see marked increases in global penetration particularly of the power generation mix, rising from 2.5% in 2007 to 8.6% in 2030, with wind power showing the greatest absolute increase in market share (International Energy Agency 2011).

Available energy from the seas and the air above them greatly exceeds current total human energy usage (Edenhofer et al. 2012). However, harnessing that energy presents a number of technological challenges and virtually all of the energy resources exhibit some form of dependence on the global climate system. Thus we address the following questions:

1. What is the estimated resource for wind, wave, tidal, or sea currents, and what is the current status of technology deployment to harness those resources?

2. How susceptible are those resources to climate change? That is, what impact might global climate change, including changes in the frequency and/or intensity of extreme events, have on wind, wave, tidal, or sea currents, the magnitude of the resources, or our ability to harness those resources?

Further, where possible, we indicate what actions (adaptation/mitigation) might be undertaken to minimize/eliminate the negative consequences of large-scale implementation of these technologies and/or potential impacts of climate change or to take advantage of the opportunities provided thereby.

3.04.2 Resource Estimates and Status of Deployment

A synthesis for all renewable technologies as developed by the IEA is given in Table 1; other estimates are available from the recently released Intergovernmental Panel on Climate Change (IPCC) report on renewable energy sources (Edenhofer et al. 2012). Specific resource estimates for the ocean energy technologies described herein are given below. Key challenges to making these types of resource estimates for any renewable source are as follows:

- The resource potential is not fixed, but rather is a function of the technology available, economics and assumptions regarding constraints to developing the resource.
- Potential resources can be computed on the basis of a range of different assumptions. The theoretical potential resource is an estimate of the total energy in the fluid under consideration, while the technical potential resource accounts for geographical constraints to harnessing the resource and losses in the energy conversion (Hoogwijk et al. 2004). Thus the former will exceed the latter.

In part because of the challenges articulated above, resource estimates exhibit large variability from analysis to analysis (Edenhofer et al. 2012). Nevertheless, prior analyses have indicated that the marine energy sources could make a substantial contribution toward electricity supply in many countries (del Rio 2011). For example, one analysis of the UK wave and tidal resources indicated realistic target contributions to electricity supply of 75 TWh year^{-1} (Kerr 2005), which equates to approximately one-quarter of the current demand in the United Kingdom (UK Department of Energy and Climate Change 2010), and approximately 20% of Denmark's electricity supply already derives from wind power plants, with about one-third from offshore installations.

Table 1 Total global realizable resource potentials for renewable technologies in the medium term (i.e., by the 2020s) (International Energy Agency 2008)

Technology	*Resource (in TWh)*
Biogas	644
Solid biomass	1841
Municipal waste	258
Geothermal electricity	87
Hydropower	4041
Solar photovoltaic	394
Solar thermal electricity	91
Tidal and wave energy	156
Onshore wind	962
Offshore wind	443

Data from International Energy Agency, 2008: *Deploying Renewables: Principles for Effective Policies*, OECD/IEA. [Available online from http://www.iea.org/publications/free_ new_Desc.asp?PUBS_ID=2046.]

Despite earlier progress on other technologies that rely upon harnessing energy from thermal or salient gradients (Duguay 1977) and the development of some demonstration projects (Vega 2003), the primary mechanisms for harnessing ocean renewable energy considered here involve deployment of devices to convert the kinetic energy in wind, wave, tidal, or sea currents into electrical power (Barthelmie et al. 2000; Bedard et al. 2010). A fairly recent review of US projects in all the water power technologies is given in a recent report from the U.S. Department of Energy (U.S. Department of Energy: Office of Energy Efficiency and Renewable Energy 2009).

3.04.2.1 Wind Energy

3.04.2.1.1 Harnessing the Power of the Wind

The potential harnessable power in the wind at any moment is given by

$$E = \frac{1}{2}\rho U^3 \qquad [1]$$

where

E is the energy density

ρ is the air density

U is the wind speed at hub-height

The actual electrical power production from a wind turbine is a nonlinear function of the incident wind speed and is described using a turbine specific 'power curve.' A turbine power curve describes the relationship between hub-height wind speed and electrical power produced. At low wind speeds below 'cut-in,' no electrical power is produced. Power production increases rapidly as wind speeds exceed the cut-in (which is typically approximately 4 m s^{-1}), to achieve rated power (the rated capacity of the wind turbine) at wind speeds of approximately 15 m s^{-1}. A further increase of the wind speed does not increase the electrical power production and at excess wind speeds (typically above approximately 25 m s^{-1}) electrical power production ceases (although this condition is realized only very infrequently at currently operating wind power plants). Thus actual power production from wind turbines is dominated by the upper percentiles of the wind speed probability distribution. For a typical high-wind speed site suitable for wind energy development up to 90% of the electricity is produced by the highest 50% of wind speeds and one-quarter of electricity generated derives from the highest 10% of wind speeds (Pryor and Barthelmie 2010).

Wind turbines convert the kinetic energy in the atmospheric flow into mechanical energy typically by harnessing the rotation of aerodynamically blades into faster-rotating gears. While a number of designs have been tested, most commercial machines use three blades arranged on a horizontal axis wind turbine wherein as the wind passes over the blades, lift is created causing the rotor to turn. This mechanical energy is then converted into electricity using a generator (Barthelmie et al. 2000; Manwell et al. 2002). The maximum power that may be extracted by a wind or tidal current turbine is approximately 59%. At this aerodynamic efficiency, the wind speed directly behind the wind turbine is approximately one-third of the incident wind speed at hub-height (DNV/Risø 2002).

3.04.2.1.2 Resource Magnitude

There are a range of estimates of the global wind energy resource magnitude, but the current technical potential resource was estimated to be 840 PWh year^{-1} even when only offshore regions with water depths >200 m were excluded, and a capacity factor of 20% was applied (Lu et al. 2009). This exceeds current worldwide consumption of electricity by 40-fold (Lu et al. 2009). Even if lower estimates of 110 PWh year^{-1} (Krewitt et al. 2009) prove more accurate, the total resource is substantial.

Wind speeds offshore are typically of greater magnitude and more persistent than at geographically proximal land sites leading to higher capacity factors (i.e., ratio of actual output from a power plant over a period of time to the potential output if it had operated at full rated capacity for the entire period) at offshore locations (Pryor and Barthelmie 2001). Thus even confining analyses to the near shore region, a substantial fraction of both the theoretical and technically feasible resources, lie offshore (Lu et al. 2009) (Table 1).

3.04.2.1.3 Current Status of Wind Energy Deployment

Installed wind energy capacity rose from approximately 94 GW in 2007 (Milford 2008) to nearly 121 GW in 2008 (News 2009), and over 197 GW by the end of 2010 (Global Wind Energy Council 2011). It has been suggested that installed capacity may equal 400 GW by 2014 (Global Wind Energy Council 2011), and exceed 700 GW by 2017 (de Vries 2008).

Europe is currently the global leader in offshore wind installations with nearly 1.5 GW installed in European waters in 2008 (de Vries 2009) (Table 2), and during 2010 of the nearly 9.3 GW of wind energy installed in the EU-27 during 2010, almost 1 GW was installed offshore (Global Wind Energy Council 2011). In one global analysis conducted by the IEA, electricity generation from wind power (including offshore wind plants) is projected to reach 4.5% of total global generation in 2030 compared to less than 1% in 2007 (International Energy Agency 2011).

Table 2 National offshore wind energy capacity within the European Union in 2008 and estimated national projections for 2020 (Green and Vasilakos 2011)

Country	*2008 Capacity (GW)*	*2020 National plan (GW)*
United Kingdom	0.59	13
Germany	0.01	10
France	–	6
Netherlands	0.25	5.18
Sweden	0.13	1.82
Denmark	0.41	1.34
Belgium	0.03	1.8
Spain	–	3
Finland	0.02	–
Ireland	0.03	0.6
Italy	–	0.7
Poland	–	0.5
Greece	–	0.3
Estonia	–	0
Latvia	–	0
Lithuania	–	0
Others	–	1
EU-27	1.47	45.2

Data from Green, R., and N. Vasilakos, 2011: The economics of offshore wind. *Energy Policy*, **39**, 496–502.

The European Union market for onshore wind energy grew by an average 32% per year from 1992 to 2004 (European Wind Energy Association 2009b) and has continued to experience sustained investment (Figure 1). In order to achieve either the European Union (EU) goal of 20% of energy from renewable by 2020 or the European Wind Energy Association (EWEA) target of 40 GW of offshore wind in the EU by 2020, similar expansion of the exploitation of vast offshore wind resources will be required. Assuming this level of growth, cumulative offshore installed wind capacity in Europe may reach 40 GW by 2020 and 150 GW in 2030 (de Vries 2009) (Table 2). Although in the near-term, the United Kingdom and Germany will likely to continue to make the greatest investments in offshore installations (Figure 2 and Table 2), other countries are also increasingly seeking to develop offshore wind power plants (de Vries 2009), and the first offshore wind farm in China began generation in the summer of 2010 (Global Wind Energy Council 2011).

Virtually all wind turbines that have been installed offshore to date have been deployed in relatively shallow waters (<20 m) and use either monopole, tripod, or gravity base foundations (Abbatt and Molina 1993; Dabberdt et al. 1993; DNV/Risø 2002; European Wind Energy Association 2009a). Much of the offshore wind resource lies in deep waters where hydrodynamic loads will likely be higher and floating support platforms may be the optimal support structure (European Wind Energy Association 2009a; Henderson 2009; Jonkman 2009).

3.04.2.2 Wave Energy

3.04.2.2.1 Harnessing the Power of Waves

Water waves observed in the field are the result of combined mechanics of wave generation, dissipation, propagation, and nonlinear wave–wave interactions. The primary generation mechanism is friction from the overlying atmosphere and thus the state of the sea is related to the in situ atmospheric conditions. However, the coupling is complex and bidirectional. The growth rate of waves is proportional to the square of the friction velocity (which is a metric of momentum dissipation at the surface), and there is a reciprocal coupling to the atmosphere, where the roughness of the water surface (which is a function of the wave field) is a key determinant of the near surface wind speeds and the shape of the vertical profile of winds (Peña and Gryning 2008). The actual wave field is not solely a function of local production and dissipation but also includes a component from remotely generated swells (long-wavelength waves generated by distant atmospheric phenomena) (Smedman et al. 1999).

As discussed further below, wave climates are important not only to the wave energy resource, but also fatigue and extreme loading on offshore structures such as wind turbines. Under some simplifying assumptions, and in moderate water depths,

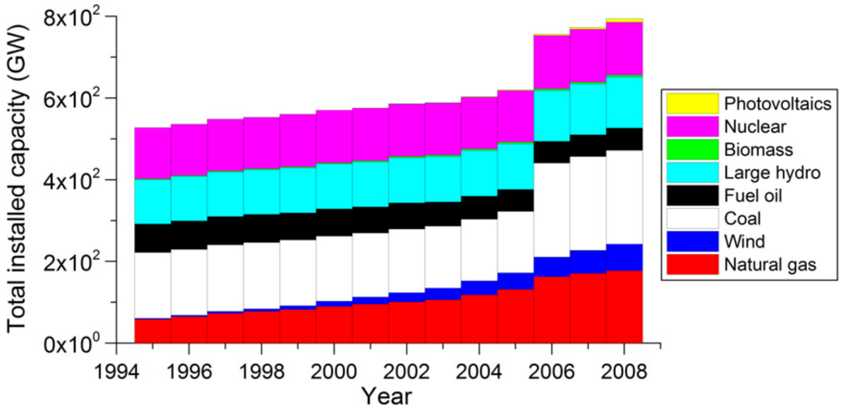

Figure 1 Total installed capacity (GW) in the European Union 1995–2008. Prior to May 2005, the data reflect the EU-15, prior to January 2007 it is the EU-25 and subsequent to that the data are drawn from the EU-27. Data taken from European Wind Energy Association E, 2009c: Pure power: wind energy targets for 2020 and 2030, EWEA. [Available online at http://www.ewea.org/fileadmin/ewea_documents/documents/publications/reports/Pure_Power_Full_Report.pdf.]

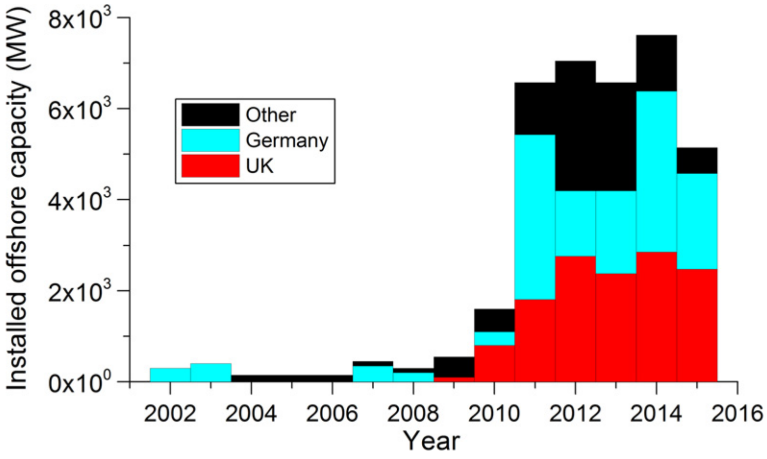

Figure 2 Recent and planned offshore wind projects (MW) by expected (or actual) commissioning date. Graph redrawn from von Bismarck et al. (2009). Also see data in **Table 2**. Reproduced from von Bismarck, M., A. Gurung, M. Liebreich, and C. Greenwood, 2009: Green investing. Towards a clean energy infrastructure. *Energy Bull.*, **3**, 6–23.

key wave characteristics can be described using Airy wave theory (US Army Corps of Engineers 2008), in which the velocity potential is given by

$$\Phi(x, y, z; T) = \frac{Hg}{2\omega_s} D(z) \sin(kx - \omega_s T) \qquad [2]$$

where

H is the wave amplitude

g is the acceleration due to gravity

ω_s is the frequency $(2\pi/T)$

$D(z)$ is the depth decay function given as

$$D(z) = \frac{\cosh[k(z+d)]}{\cosh(kd)}$$

k is the wave number $(x\cos\theta + y\sin\theta)$

λ is the wavelength

x,y are the perpendicular axes with $z = 0$ at the still water level

θ is the direction of the wave relative to the x-axis

d is the water depth

T is the wave period

For Airy waves, the horizontal velocity (u_w) and acceleration (a) are given by

$$u_w = \frac{HgT}{2\lambda} \frac{\cosh[2\pi(z+d)/\lambda]}{\cosh(2\pi d/\lambda)} \cos\theta \qquad [3]$$

$$a = \frac{HgT}{2\lambda} \frac{\sinh[2\pi(z+d)/\lambda]}{\cosh(2\pi d/\lambda)} \sin\theta \qquad [4]$$

Waves propagate at the phase speed (c_p) (i.e., at a velocity, v), which is given by

$$c_p = \frac{\omega_s}{k} = \frac{\lambda}{T} \qquad [5]$$

The actual electrical energy that can be produced by a wave energy converter (WEC) is a function of the entire directional wave spectrum (Mackay et al. 2010). However, the significant wave height H_s is a key determinant of the energy in the wave field, and may be operationally estimated as four times the standard deviation of wave height (i.e., $4\sigma(H)$). Where spectral information regarding the wave field is unavailable, for deep ocean 'Airy' waves (where the wavelength of the wave is small compared to the depth of the water) the power in the waves (the wave energy flux, P) and the average energy density per unit area of waves on the water surface (E) may be approximated using H_s and the wave period (T) as follows:

$$P = \frac{\rho g^2}{64\pi} H_s T \qquad [6]$$

$$E = \frac{\rho g}{16} H_s^2 \qquad [7]$$

H_s can also be used to approximate the most probable maximum wave height in a given sea state for 1000 waves using (van der Temple 2009)

$$H_{\max} = 1.86 H_s \qquad [8]$$

Naturally, the wave field is also a function of bathymetry and as waves approach the shoreline the seabed begins to influence their speed such that at water depths less than one-quarter of the wavelength, the wave velocity (v) is

$$v = \sqrt{gd} \qquad [9]$$

As with wind turbines, wave power technologies capture part of this energy and reduce wave heights in the lee of the device. However, unlike wind, there is no single preeminent technological solution to harnessing energy from waves and tidal currents (Barthelmie et al. 2000; Mueller and Wallace 2008; Price 2009; Heath 2012). Kinetic wave energy devices generally fall into one of three classes:

- Attenuators, wherein long multisegment floating structures are placed in parallel to the direction of the waves. Flexing of the structures due to the passage of waves causes expansion and contraction of segment connections, which power hydraulic pumps and a generator.
- Point absorbers, where a floating device (e.g., a floating buoy within a fixed cylinder) absorbs energy from the oscillation of the water surface causing a stretching and compressing motion, which is used to drive electromechanical or hydraulic energy converters.
- Termination wave devices, in which water enters through a subsurface opening into a chamber with air trapped above it, the rise and fall of the water within the chamber acts like a piston forcing air through an opening connected to a turbine, which then generates electricity.

An additional class of device relies on using wave overtopping to collect water that then flows through a traditional low-head hydropower turbine. While these were originally coastal type devices like the TAPCHAN prototype in Norway, it is also the mechanism used by the Wave Dragon (Tedd and Kofoed 2009).

3.04.2.2.2 Resource Magnitude

The range of estimated theoretical wave energy resource potentials available in the literature is comparatively large. One estimate of theoretical potentials for wave energy of 7400 EJ (Exa-J = 10^{18} J, equivalent to 234 TWh year^{-1}) was approximately equal to that for wind energy (Resch et al. 2008). Due to the comparative nascent status of wave energy deployment it is difficult to assess the global technical resource with any confidence, but one analysis determined that it exceeds 2.7 TW (Jacobson and Delucchi 2011). **Table 3** summarizes one analysis of the technically achievable wave power resource (Frefri and Infield 2008). This assessment is in accord with that of Jacobson and Delucchi (2011) if the far offshore is included.

Table 3 Total global technically achievable wave power resource (Frefri and Infield 2008)

Location	*Global potential (GW)*
Shoreline	1–50
Near shore	10–500
Offshore	200–5000

Data from Frefri, L., and D. Infield, 2008: *Renewable Energy in Power Systems*, John Wiley and Sons, Ltd., Chichester, U.K.

As with the wind resource there is tremendous spatial variability in wave energy density (Arinaga and Cheung, 2012). One global analysis of wave energy resources found largest resources in the latitude zone 40–60°S, and specifically off the SW coast of Australia where maximum wave energy flux exceeds 125 kW m^{-1} of wave crest. In the northern hemisphere, the highest average wave power is focused on regions within the North Atlantic – specifically off the coast of Iceland and to the west of the British Isles (Cornett 2009; Arinaga and Cheung 2012). Many individual countries and regions have also assessed the available wave energy resource (Zhang et al. 2009; Hughes and Heap 2010; Lenee-Bluhm et al. 2011).

Naturally, like the energy density of the near surface atmospheric flow, the wave field (and by association the wave energy density) at a specific location exhibits variability on a wide range of time scales from seconds to decades, though in the case of waves the high frequency variability is suppressed relative to the atmosphere.

3.04.2.2.3 Current Status of Wave Energy Deployment

Wave energy projects are largely in the research and demonstration phase and indeed a number of large-scale wave energy prototypes have been tested (Cruz et al. 2008; Mueller and Wallace 2008). In 2008, the world's first wave commercial-scale power plant was developed off the coast of Portugal at Aguçadoura. The first phase of the development uses attenuator technology and has a capacity of 2.25 MW. Due to technical and financial issues the project was delayed, but plans are underway to expand the project under new management. Further devices from the same company (Pelamis) are under test at the European Marine Energy Center in Shetland, UK. Point absorber technology has been used by Ocean Power Technology (OPT) with their power buoy that was deployed off Oahu, Hawaii, and grid connected in 2010. A 500 kW system based on the oscillating water column concept has been in operation since 2000 on the Scottish island of Islay (Heath 2012). A new round of investment in wave energy technologies is expected, but issues of the cost of electricity, reliability, and durability of the devices and project finance continue to hamper larger scale developments and deployment (Renewable Energy World 2011).

3.04.2.3 Tidal and Sea Currents

3.04.2.3.1 Harnessing the Power of Tides and Sea Currents

Tides are cyclic variations in the level of water bodies due principally to the gravitational force of the moon. Thus one advantage of tidal energy over other ocean renewable resources is it is highly predictable (Jahromi et al. 2011). Two approaches are available to harness tidal power; the first relies on deployment of barrages to establish a head of water, which can power a turbine (and thus to work in a manner similar to most hydroelectric schemes), and the second approach harnesses local tidal currents and thus exploits the water currents associated with tides (Barthelmie et al. 2000; Blanchfield et al. 2008; Denny 2009; Rourke et al. 2010; Atwater and Lawrence 2011).

Tidal turbines share many similarities to wind turbines; however, due to the higher density of sea water they can produce 800–900 times more power when compared to an equivalent wind turbine of similar size operating at the same speed (Jahromi et al. 2011). A wide range of possible technologies have been proposed to determined the magnitude of the tidal current resource and to harness tidal currents (Walkington and Burrows 2009; Rourke et al. 2010), but as discussed below, these are currently in the demonstration phase.

The energy available from a tidal barrage is given by

$$E = \frac{1}{2}A\rho g h^2 \qquad [10]$$

where

A is the horizontal area of the barrage basin

h is the range in water level from high to low tide

Ocean currents can additionally be harnessed (Bernitsas et al. 2008; Bahaj 2012) and have the advantage that they are relatively well predicted since they are largely gravitationally forced. The theoretical resource has been estimated to be 5 TWh (Tester et al. 2005). However, there are no commercial grid-connected turbines generating electricity from ocean (or sea) currents currently and thus they will not be discussed further here.

3.04.2.3.2 Resource Magnitude

It is difficult to assess the total global tidal resource, but one estimate suggests that the potential mean power and potential annual electricity production from tidal barrage sites that have been extensively surveyed to date exceed 65 TWh and 600 TWh year^{-1}, respectively (Rourke et al. 2010). The theoretical potential tidal resource as estimated by the IEA exceeds 800 TWh year^{-1} Table 4 (IEA/OECD 2007). The tidal resource is highly spatially variable, but countries with large estimated resources include the United Kingdom, Ireland, Canada, and China (Burrows et al. 2009; O'Rourke et al. 2010). For example, in Ireland, tidal power could contribute up to 10% of national electricity use (O'Rourke et al. 2010) and the total theoretical potential tidal resource along the coastline of China has been estimated to exceed 580 TWh year^{-1} (Liu et al. 2011).

Table 4 Comparison of potential global electricity production estimates from ocean energy sources (IEA/OECD, 2007). For comparison, the theoretical total wave energy potential was estimated to be 29 500 TWh year^{-1} in the 2012 IPCC summary, while the thermal energy resource was estimated to fall toward the lower end of a cited range of 30 000–90 000 TWh year^{-1} (Edenhofer et al., 2012)

Method	*Potential production (TWh year^{-1})*
Tidal current	>800
Salinity gradient	2000
Ocean wave	8000–80 000
Thermal energy	10 000

Data from IEA/OECD, 2007: *Energy Technologies at the Cutting Edge*. International Energy Technology Collaboration–IEA Implementing Agreements, Paris, France.

3.04.2.3.3 Current Status of Tidal Power

According to some estimates, the cost assessments for tidal barrages generally indicate economic feasibility at about 5 m tidal range (Price 2009). The only large-scale tidal barrage power plant was built in La Rance, France in 1966. The mean tidal range at this site is 7 m and the tidal power station has an installed capacity of 240 MW. The approximate annual electricity production from this tidal barrage is 544 GWh (Kerr 2005). The next largest facility is located at Annapolis Royal, in Nova Scotia. Built in 1984, it has a capacity equal to 18 MW (Rourke et al. 2010). A further large (254 MW) tidal barrage project in Korea was projected to be completed in 2010 (Bae et al. 2010), but remains unfinished as of early 2012. There are also several smaller projects in China (Liu et al. 2011) and Atlantis Resources recently announced it will install a 50 MW tidal farm in the Gulf of Kutch on India's west coast, with construction starting early in 2012. Other locations for tidal barrages have been proposed and sites for development including the Bay of Fundy in Canada, which has a tidal range of 10 m and the Severn Estuary in the United Kingdom (Clery 2008), which has a mean tidal range of 8 m (Barthelmie et al. 2000). A number of smaller capacity tidal stream energy converters have been deployed, including a 1.2 MW device in Strangford Lough, Northern Ireland (Atwater and Lawrence 2011; Devine-Wright 2011). China has also deployed several small-scale devices including both bottom-mounted and floating devices (Goa 2011).

In the global analysis of the IEA, tidal and wave energy produced just 0.6 TWh of electricity in 2007, but it was projected to increase to almost 13 TWh by 2030 (International Energy Agency 2011).

3.04.2.4 Current Challenges to Large-Scale Deployment of Renewable Ocean Technologies

A number of challenges confront large-scale implementation of technologies to harness ocean energy resources. These include but are not limited to intermittency, cost, and environmental impacts. Brief description of, and possible mitigation options for, these issues is given below.

Virtually all renewable energy resources exhibit some degree of intermittency. Addressing issues of intermittency indeed may be key to facilitating achievement of the goals and projections for ocean energy technologies articulated by the IEA and others. Concerns over the security of electric supply, combined with increasing pressure to tackle climate change, have forced many European countries to urgently reevaluate their energy strategies, and to propose a pan-European electricity Supergrid to act as a transmission network (Macilwain 2010), enabling the secure distribution of electricity between countries and to facilitate flexibility in electricity generation and supply management. It is often argued that introduction of large-scale wind or wave power will lead to excessive demand for spinning reserve due to intermittency of supply. However, given the spatial scales of synoptic-scale weather systems, the spatial autocorrelation function for wind is only a few hundreds of kilometers (Pryor et al. 2006a), thus a distributed and highly interconnected network exhibits much smaller temporal variability in electricity supply. Enhancing the distribution network as proposed with the Supergrid will not only facilitate integration of renewable energy supplies, but may also increase resilience to extreme events (e.g., extreme wind storms). Such policies could also be coupled with local actions such as deployment of increased smart-metering systems (Zhang and Nuttall 2011) that coupled with dynamical (real-time) pricing regimes allow consumers (private and commercial) to determine usage based on price. Although refinements may be necessary for full-scale operation, this mechanism has been shown to be effective in moderating peak demand in small-scale deployments (Strengers 2010). An alternative strategy to issues of deliverability of electricity is to deploy storage technologies. At least some of these technologies are coincident or complementary with ocean renewable energy converters, for example, where technologies are deployed that can store water until electricity demand exceeds some threshold, at which point it is released to increase electricity supply (Clarke et al. 2006; Price 2009).

Externalities and other considerations influence actual energy policy, but cost is a vital component of the adoption of any technology. However, pricing is a function of complex subsidies, discounting rates and assumptions regarding fuel costs. Typically for the renewable energy technologies the majority of the costs are upfront capital costs while the fuel is free. Thus the degree to which future expenditures or costs are related to current value is critical to assessing the average lifetime cost per megawatt hour of a given electricity source (Allan et al. 2011). There is a need, therefore, to ensure robust benchmarks, externality costs, and full life-cycle analyses are applied when assessing the economic viability of different electricity generation technologies.

All energy sources for electricity generation result in environmental impacts and other externalities (Gohlke et al. 2011). Possible impacts of deployment of ocean renewable technologies generally fall within four principal areas of concern: (i) acoustics and specifically noise (which is largely confined to the construction phase), (ii) introduction of electromagnetic fields, which can be minimized (though not completely eliminated) by shielding of cables, (iii) alteration of the dynamics of the environment via obstruction to the flow and possible collision of organisms with support structures, and (iv) alteration of local species composition (Gill 2005). Accordingly, environmental impact assessments are routinely conducted for offshore wind deployments, tidal barrages, and deployment of wave technologies (Boehlert and Gill 2010).

Naturally not all impacts on the marine environment can be eliminated, but equally not all impacts may be negative. For example, tidal barrages greatly alter the ecology of the tidal estuary, but these changes lead to both benefits and negative impacts depending on the species under consideration (Price 2009). Analyses of existing offshore wind farms in Denmark have indicated fewer negative ecological consequences than were projected during the planning phase in terms of, for example, the impact of noise on marine mammals (Tougaard et al. 2009) and alterations of bird migration trajectories (Masden et al. 2009). Further, according to some assessments, large-scale deployment of wave technologies with appropriate planning, mitigation, monitoring etc. have the potential to offer benefits to marine birds in the future (Grecian et al. 2010). Technological advances, harmonization of environmental impact assessments, and setting of uniform standards will likely assist in optimal siting and technology design/implementation to minimize environmental effects from deployment of the ocean renewable technologies.

3.04.3 How Might Changes in Climate Statistics Influence Ocean Renewable Energy?

As discussed in Section 3.04.2 Resource Estimates and Status of Deployment, other than hydropower, wind power is the most mature and has the greatest global penetration of electricity generation of current renewable sources, thus much of the remainder of this chapter will focus on wind energy.

3.04.3.1 Changes in the Resource Magnitude

Alterations in local and regional climates may impact ocean renewable energy industries by changing the geographic distribution and/or the inter- and intra-annual variability of the resource. Relative to wind and wave energy, the influence of climate nonstationarity on tidal resources is likely only to be very modest, and would likely derive principally from changes in operating conditions (see Section 3.04.2).

As described above, wind and wave climates are highly coupled physically. Since the wind and wave resource are strongly linked to atmospheric circulation patterns, changes in the spatial–temporal distribution of resources is possible (Weisse and von Storch 2010). However, at least within the midlatitudes the dynamical linkages between any changes in climatology and the near surface flow are complex. In midlatitude regions where the atmospheric flow is not dominated by thermotopographic effects, the wind climate is principally determined by the synoptic-scale circulation and thus transitory anticyclone and cyclones. Cyclone development is a baroclinic process and thus it is relatively insensitive to large-scale (equator to pole) temperature gradients and may be more strongly influenced by upper tropospheric thermal gradients than possible decreases in near surface temperature gradients (Held 1993). Steering of those systems is influenced by the large-scale thermal gradient, but this link is also indirect, and there may be a stronger influence of higher water-holding capacity and energy availability due to the phase transfer of water (Chang et al. 2002), or changes in atmospheric stability due to changing land cover. For these and other reasons, storm track activity cannot be related directly to global-mean surface temperature or large-scale gradients therein (O'Gorman 2011). Thus it is difficult to predict apriori how climatic variability or trends in the coming decades may be manifest in terms of changing ocean energy resources. In the following subsections, we summarize some of the research that has been conducted to date regarding possible impacts of climate nonstationarity on ocean energy resources.

3.04.3.1.1 Historical Tendencies and Variability

Assigning causality to temporal tendencies in wind or wave climates is very difficult. Key challenges to understanding how climate nonstationarity has or may influence the spatial and temporal distribution of wind and wave climates and thus the wind and wave resource, derive from the large inherent variability in many locations and a lack of complete understanding the sources of current variability in near surface wind regimes (and by association wave climates).

Although the magnitude of the temporal trends in ocean winds and waves is sensitive to the precise data set used and data homogenization procedures applied (Tokinaga and Xie 2011a; Wentz and Ricciardulli 2011; Young et al. 2011a,b), the majority of analyses of recent historical tendencies in oceanic near surface wind speeds and wave climates have generally indicated trends toward increased values. For example, an analysis of wind speeds and wave heights from a 23 year record of satellite altimeter measurements indicate increasing wind speeds over the majority of the world's oceans (of up to 5% per decade for 1991–2008) (Young et al. 2011b). The same study found a smaller magnitude increases in mean significant wave height, though the tendencies were not statistically significant. Extreme values (99th percentile values) of both parameters also exhibited increases. In the case of 99th percentile significant wave height, the tendencies were mostly positive in the North Atlantic, particularly off the coast of Europe (Young et al. 2011b). Based on data from passive microwave satellites, another analysis found that average over all oceans the trend in wind speeds was $+0.08\ \mathrm{m\ s^{-1}\ decade^{-1}}$ (1.0% per decade) during 1987–2006 (Wentz et al. 2007). There is some evidence of a weakening of trade winds over the tropics (Tokinaga and Xie 2011b), but positive tendencies have generally been found to be largest in the higher latitudes (Wentz et al. 2007; Young et al. 2011b). There is also some evidence from deep water wave buoys for increased mean significant wave height in the north Pacific during the last three decades and for an increase in mean wave energy along the west coast of North America (Seymour 2011). Conversely, an analysis of wave climates in the northwestern Mediterranean Sea over the last 44 years found no significant temporal trends in annual mean and maximum energy, but an increase in the storm energy of events from the south (Casas-Prat and Sierra 2010).

Because the wave field is not instantaneously coupled to the atmospheric flow and is a function not only of wind speed, but also, for example, wind direction due to the influence on over–water fetch, tendencies in wind and wave fields need not be linearly related. For example, one analysis of future wave heights in the North Sea indicated evidence for increases of 18%, while the 99th percentile wind speed increased by only 7% (Grabemann and Weisse 2008). Further, an analysis using the third-generation wave model WAM over the Baltic Sea for 1970–2007 found that when wind fields constructed on the basis of geostrophic winds were applied to the WAM model, a complex spatial pattern of changes in basic wave properties (average and extreme wave heights and wave periods) evolved. The study found annual mean significant wave height decreased by more than 10% in the south of the Baltic Sea (off the coast of Poland) over the period 1970–2007, but increased along the German coastline by an equivalent fraction (Soomere and Raamet 2011).

A number of studies have examined possible changes in the number, intensity, or location of storm tracks (preferred regions of extra-tropical cyclone activity) and have found extra-tropical cyclone activity is strongly related to large-scale modes of climate variability (e.g., El Niño-Southern Oscillation (ENSO), the Arctic Oscillation (AO), the North Atlantic Oscillation (NAO), the Pacific–North American (PNA) index, and others), which results in large intra-annual, inter-annual, and even inter-decadal variability in storm activity which is also manifest in wind and wave climates (Weisse and von Storch 2010). For example, inter-annual variability in wind energy density across much of Europe is of the order of ±10–15%, while the inter-decadal variability is approximately ±30% (Pryor and Barthelmie 2010). This time-scale of variability is particularly marked in the midlatitude regions influenced by storm tracks and greatly confounds detection of a climate change signal. A strong signal for continued influence of internal climate variability is also manifest in wind regimes over Europe drawn from climate simulations of the 20th century (Pryor et al. 2012a).

3.04.3.1.2 Future Scenarios

Developing scenarios of possible future wind and wave resources is challenging. The ability of dynamical or statistical downscaling tools to generate robust higher resolution scenarios of near surface climate parameters in the coming decades from climate simulations conducted using coupled Atmosphere–Ocean General Circulation Models (AOGCMs) has been challenged (Pielke and Wilby 2012). Some analyses have indicated downscaling tools applied to wind climates exhibit some skill the historical period particularly over the land surfaces and in the coastal zone (Winterfeldt et al. 2011; Pryor and Barthelmie 2012a; Pryor et al. 2012b,c). However, the variability in wind climate projections for future periods due to variability in the AOGCMs and downscaling methodology applied is of comparable magnitude to the climate change signal present in future simulations (Pryor et al. 2005a,b, 2009; Pryor and Schoof 2010; Pryor and Barthelmie 2011) (see **Table 5**). Further, while model transferability experiments have demonstrated that Regional Climate Models (RCMs) can simulate some climate conditions beyond those in the historical period in the region of origin (e.g., Jacob et al. 2012), there remain concerns about the ability of the model-chains to capture possible changes in the climatology of near surface parameters. Thus the scenarios provided in Sections 3.04.1 and 3.04.2 should be interpreted as providing, at best, a subset of possible future conditions.

It is important to note that AOGCMs are variable in their ability to reproduce the modes of inter-annual variability (e.g., the teleconnection indices describe above) (Stoner et al. 2009; Harding et al. 2011), and that AOGCMs tend to underestimate both inter-annual and intra-annual variabilities of near surface wind speeds relative to those from reanalysis data sets (Chen et al. 2012). Further, wind and wave climates in the coastal zone vary on temporal and spatial scales below those typical of climate models (Barthelmie et al. 2007). With those caveats in mind, research to date suggests multiyear annual mean wind power densities over Europe and North America will likely remain within ±25% of historical values during the current century (Breslow and Sailor 2002; Pryor et al. 2005a, 2006b;

Table 5 Sensitivities of downscaled 90th percentile wind speed (used as an analog for the wind energy density) for 46 stations across Northern Europe from the probabilistic approach of Pryor et al., (2005b). The results show the total range of differences in the 90th percentile wind speed computed for 2081–2100 versus 1961–1990. Thus if the range is ±*X*%, at all stations the projected period lies with *X*% of conditions during the historical period. Table adapted from Pryor and Schoof (2010)

Parameter	*# AOGCMs*	*SRES*	*Range of estimates*
AOGCM architecture	10	A2	±25% for 45 of 46 stations
Stochastic w/in AOGCM	5 (Copenhagen station)	A2	95% of realizations w/in ±10%
SRES	1 (ECHAM5)	A2, A1B, B1, Commit	±15%
AOGCM member	1 (ECHAM5)	2 × 20th century	±15%

Key of uncertainties assessed: (i) AOGCM architecture: i.e., variations in the downscaled results computed over all stations for downscaling using output from 10-AOGCMs. These variations reflect the influence of the AOGCM from which the predictors were obtained. (ii) Stochastic w/in AOGCM: i.e., variations in the downscaled results computed over all stations that derive from 1000 bootstrapped resampled time series of the predictors. These variations reflect the influence of white noise in a given AOGCM simulation. (iii) SRES: i.e., the emission scenario applied in the AOGCM simulations. (iv) AOGCM member: i.e., the variation that derives from differences in the AOGCM predictors, due to small perturbations in the conditions from which the AOCGM evolves.

Modified from Pryor, S. C., and J. T. Schoof, 2010: Importance of the SRES in projections of climate change impacts on near-surface wind regimes. *Meteorol. Z.*, **19**, 267–274.

Walter et al. 2006; Bloom et al. 2008; Sailor et al. 2008; Pryor and Schoof 2010; Pryor and Barthelmie 2011). Using output from the RCM simulations conducted under the North American Regional Climate Change Assessment Program (NARCCAP) (Mearns et al. 2009), mean annual energy density (at a nominal height of 10-m) for 2041–2062 was computed for all partly or totally offshore grid cells within 100 km of the US coast. The two RCM–AOGCM combinations selected for this analysis are RegCM3 = Regional Climate Model 3 (Pal et al. 2007) nested in the GFDL = Geophysical Fluid Dynamics Laboratory model (CM2.1) (Delworth et al. 2006) and CRCM = Canadian Regional Climate Model (de Elia and Cote 2010), nested in CGCM3 = Canadian model Version 3 (Scinocca et al. 2008). Both of these model combinations exhibit mean energy density fields over North America that exhibit a relatively high degree of accord with independent wind resource estimates (Pryor and Barthelmie 2011). The results of analyses of the difference in grid-cell averaged energy density in simulations of 2041–62 relative to 1979–2000 indicate that the projected mean energy density at the majority of coastal locations lies within 10% of historical values (**Figure 3**). However, this analysis also reemphasizes the importance of the precise

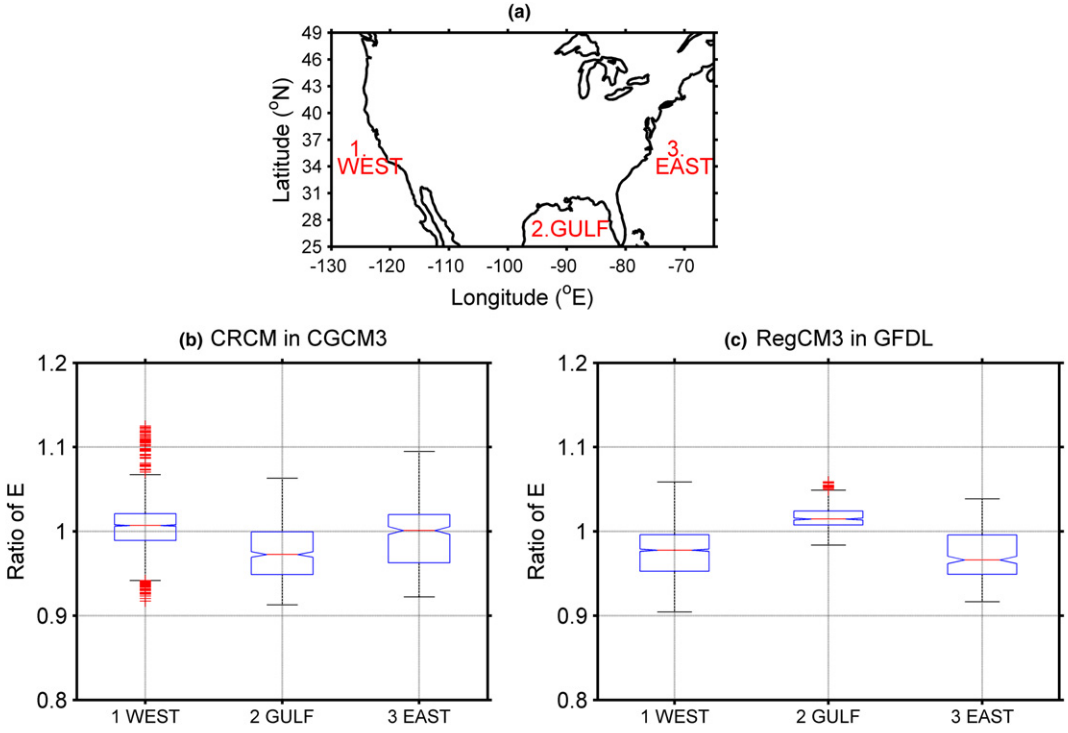

Figure 3 Box-plots of the ratio of energy density (2041–62 versus 1979–2000) in coastal grid cells (i.e., grid cells within 100 km of the coastline) in simulations from (b) Regional Climate Model 3 (RegCM3) nested in the Geophysical Fluid Dynamics Laboratory (CM2.1) AOGCM and (c) Canadian Regional Climate Model (CRCM) nested in the Canadian AOGCM version 3 (CGCM3). These simulations were conducted under the North American Regional Climate Change Assessment Program (NARCCAP), and the future period assumes greenhouse gas emissions according to the A2 SRES. Frame (a) shows the regions used to summarize the data in frames (b) and (c).

AOGCM–RCM combination used in the scenario development in determining the sign and magnitude of change. In simulations using the CRCM coupled to the CGCM3 AOGCM, the majority of locations along the West Coast of the USA exhibit marginally higher energy density in the mid-century, while in the simulations from RegCM3 nested within GFDL AOGCM the converse is true (**Figure 3**). Also, in both sets of simulations, the climate change signal is considerably smaller than the inter-annual variability in the historical period 1979–2000. Naturally, this does not imply wind resources in the water surrounding the contiguous USA will not deviate from historical values, but at least in the medium term (i.e., the mid-21st century) these model simulations do not indicate evidence for substantial changes.

Climate change analyses that have been conducted to date with a focus on sea state generally indicate projected increases in wave activity in the Northeast Atlantic. One study reported the current 20 year return period wave may be expected to occur every 4–12 years by 2080 (Wang et al. 2004). In the Baltic Sea another study found that the annual mean significant wave height and the 90th percentile wave height may increase by about 0–0.4 and 0–0.5 m, respectively, over the course of the 21st century (Meier 2006). In contrast, simulations for the Mediterranean Sea using the WAM model mainly indicated lower significant wave heights under future climate change scenarios (Lionello et al. 2008). These changes are indicative of (and consistent with) an observed tendency in the majority of AOGCMs to displace storm tracks northward over the North Atlantic under most reasonable climate forcing scenarios (Bengtsson et al. 2006; Giorgi and Lionello 2008). A study to develop wave climates around Japan under climate change scenarios using the SWAN model found a 10% potential increase in the future wind speed of typhoons resulting from the warming of surface sea temperatures can lead to a 21% increase in the significant wave heights generated by these winds (Takagi et al. 2011).

Consistent with the discussion above regarding the relatively large uncertainties in simulating wind and wave conditions using existing climate models, it should be noted that there is not always consistency between results from different studies focused on projecting potential changes in wave height and storm surges. For example, one study of the North Sea in which wind fields from HadAM3H and ECHAM4/OPYC3 were used suggested most areas would experience an increase in significant wave height (H_s) of 5–8% by the end of the 21st century (Grabemann and Weisse 2008). However, a second study that based on a 17-member ensemble of North Sea water levels for 1950–2100 generated using a surge model of the North Sea with output from the ECHAM5/MPI-OM AOGCM forced with the A1B climate forcing scenario indicated no statistically significant change in the 10 000 year return values of surge heights along the Dutch during the 21st century (Sterl et al. 2009). A third study using the ECHAM5 indicated the majority of increases in storm surges during the 21st century may be focused in the northeast North Sea along the west cost of Denmark (Weisse et al. 2009). The last result is in accord with the majority of analyses of potential storm-surge statistics for the northwest European shelf, which have generally indicated increased storm-surge magnitudes (Weisse and von Storch 2010).

An early study which used output from the CGCM2 AOGCM indicated large magnitude changes in H_s off the West Coast of Europe during winter by the end of the century and further documented that the magnitude of changes was a strong function of the climate forcing scenario applied (Wang et al. 2004). In accord with lower wave heights and potentially more northward storm tracks, storm surges in the Mediterranean are projected to decrease in both frequency and intensity in the 21st century (Marcos et al. 2011).

Few studies have explicitly sought to quantify the impacts of climate change on wave energy generation from WEC. One analysis focused on Cornwall, UK found that changes in wind speeds when applied to a wave model found available wave power increased by 2–3% in the A1B climate forcing scenario but decreased by 1–3% in the low climate forcing scenario (B1 SRES). The WEC energy yield decreased by 2–3% in both A1B and B1 scenarios, due to the relatively low efficiency of energy extraction from steeper waves by the specific WEC considered (Reeve et al. 2011).

Whether changes in the global climate system will be manifest as changes in the inter-annual, seasonal, and/or diurnal variability of wind and/or wave resources in given locations are unclear. Wind climates in northern Europe exhibit seasonality with highest wind speeds during the winter (Rockel and Woth 2007) and some analyses of storminess in the Northeast Atlantic (1874–2007) exhibited notable differences temporal trends in winter (DJF) and summer (JJA) (Wang et al. 2009). Other analyses have indicated increases in wave heights in winter in parts of Europe with mainly decreases in wave height in the other seasons (Zacharioudaki et al. 2011). However, relatively little research has focused on potential changes in the seasonal variability of wind and wave resources, and given the inability of downscaling methods to reproduce historical wind and wave climate these projections must be viewed as highly uncertain.

In considering possible impacts of climate nonstationarity on extraction of ocean energy resources it is worthy of note that typical lifetimes of current wind installations are 20–30 years (though offshore foundations have longer lifetimes) and if climate nonstationarity leads to changes in the wind, wave, or current resource (or operating conditions) on time scales longer than a few decades, the respective industries may be able to adapt either through improved technology or by shifting the location of the energy extraction projects.

3.04.3.2 Changes in Operating Conditions

The primary mechanisms by which tidal installations might exhibit climate sensitivity derive from possible changes in sea level and the frequency and/or magnitude of storm surges. Sea level rise over the course of the 20th century was estimated to be $1.8 \pm 0.5\ \mathrm{mm\ year^{-1}}$ (i.e., 0.18 m) in the Fourth Assessment Report of the IPCC (Bernstein et al. 2007) and projections of a further 0.21–0.48 m rise have been made for the end of the 21st century (Grinsted et al. 2009). However, some hypothesize that projections of global sea level change cited in the IPCC assessment may be biased low by up to a factor of three (Rahmstorf 2007a,b, 2008, Grinsted et al. 2009), and that sea level rise along the east coast of the USA may exceed prior estimates (Yin et al. 2009).

Making detailed regional sea level projections is confounded by the influence of storm surges, atmospheric flow, and eustatic adjustments. For example, in the Baltic Sea, it has been reported that a global-mean sea level rise of 50 cm from 1990 to 2080 would lead to a sea level rise of 33–46 cm in Danish waters, and may reverse the historical decline in mean sea level in the Gulf of Finland (Graham et al. 2008). Such changes may have implications for tidal characteristics in specific locations, though such changes are likely to be small (Weisse and von Storch 2010). These changes may ultimately influence the design/operation of tidal barrages, but relatively little is known about such impacts. A discussion of the possible influence of climate nonstationarity on the frequency or intensity of storm surges is given below.

Offshore wind turbines experience site-specific environmental loads from wind, wave, sea currents, sea ice, and scour resulting in changing soil dynamics. Thus at a minimum when wind turbines are deployed offshore the extreme load cases considered in the design and selection of the turbine and foundation must include the contributions from the atmospheric and hydrologic components (Agarwal and Manuel 2008). Similar loading analyses are also crucial to wave energy devices.

The primary external conditions that influence the structural integrity of a wind turbine are the normal and extreme wind conditions. That is, loads relating to external conditions can be divided into extreme loads, which arise mainly from extreme (i.e., inherently rare) events with return periods of 1–50 years (described further below), and fatigue loads (Dekker and Pierik 1999), which are primarily determined by the mean wind speed and the standard deviation of wind speed fluctuations, which are strongly related to site turbulence levels (Frandsen 2007).

One of the key design standard criteria for wind turbines is linked to the 50 year return period 10 min sustained wind speed (U_{50yr}). Preliminary analyses from both dynamical and empirical downscaling over Northern Europe exhibit some evidence for increased magnitude of these wind speed extremes (Makkonen et al. 2007; Haugen and Iversen 2008; Pryor et al. 2012a). However, as described above, the internal variability is very large and there are substantial uncertainties in extrapolating to low probability events. As an example, an hourly average U_{50yr} was derived for RCM grid cell within a Northern European domain (51–71°N 3–33°E) using 30 year time slices from continuous simulations (1961–2100) from the HIRHAM5 RCM nested within the ECHAM5 AOGCM run for the A1B emission scenario (SRES). The 50 year return period value and associated uncertainty for each time slice was compared with the value derived for the control period (1961–90) (Pryor et al. 2012a). The fraction of the total number of grid cells that exhibits a U_{50yr} from a given 30-year period that is (i) above or below the U_{50yr} estimate from 1961 to 1990 and (ii) above or below the 95% confidence intervals on U_{50yr} estimate from 1961 to 1990 was then computed. The results of this analysis indicate that natural (inherent) variability in extreme wind speeds exceeds a climate change signal until toward the end of 21st century and that even for the last 20 years of 21st century, only a fairly small fraction of grid cells (approximately 22%) exhibit U_{50yr} that lies beyond the 95% confidence interval derived for the control period (**Figure 4**). Further the magnitude of changes (up to $+3\ \mathrm{m\ s^{-1}}$) are relatively modest compared to the uncertainty inherent in calculating U_{50yr} and are likely of lesser magnitude than the over estimation of U_{50yr} within the wind turbine design standards (Pryor and Barthelmie 2012a).

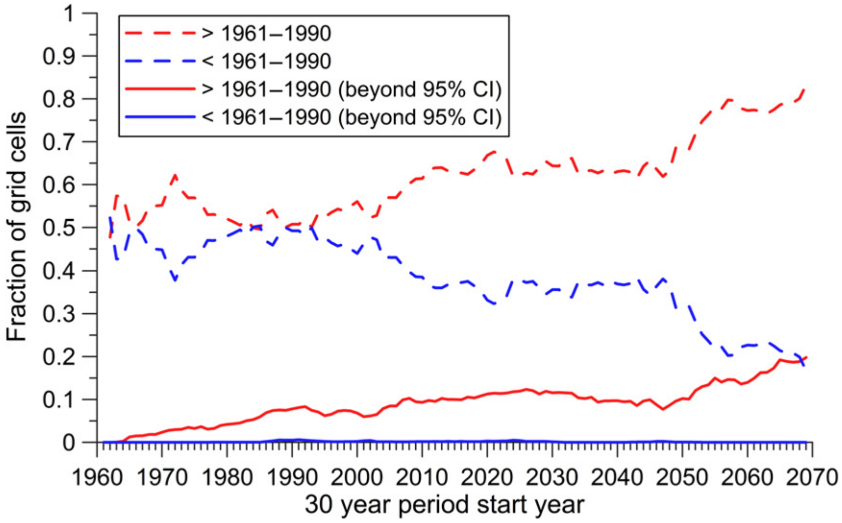

Figure 4 Fraction of the total number of grid cells in simulation of conditions over Northern Europe (51–71°N 3–33°E) using HIRHAM5 (May 2008) coupled to the ECHAM5/MPI-OM1. Atmosphere–ocean global climate model (Roeckner et al. 2006) that shows U_{50yr} above or below the value for 1961–90. U_{50yr} is computed for each grid cell and time period independently and then the data are shown as the fraction of total grid cells that show a U_{50yr} from a given 30-year period that is (i) above or below the U_{50yr} estimate from 1961 to 1990 (>1961–90 and <1961–90, respectively), and (ii) above or below the 95% confidence intervals (CI) on U_{50yr} estimate from 1961 to 1990 (beyond 95% CI). The AOGCM simulation was conducted for the A1B emission scenario (Nakicenovic and Swart 2000).

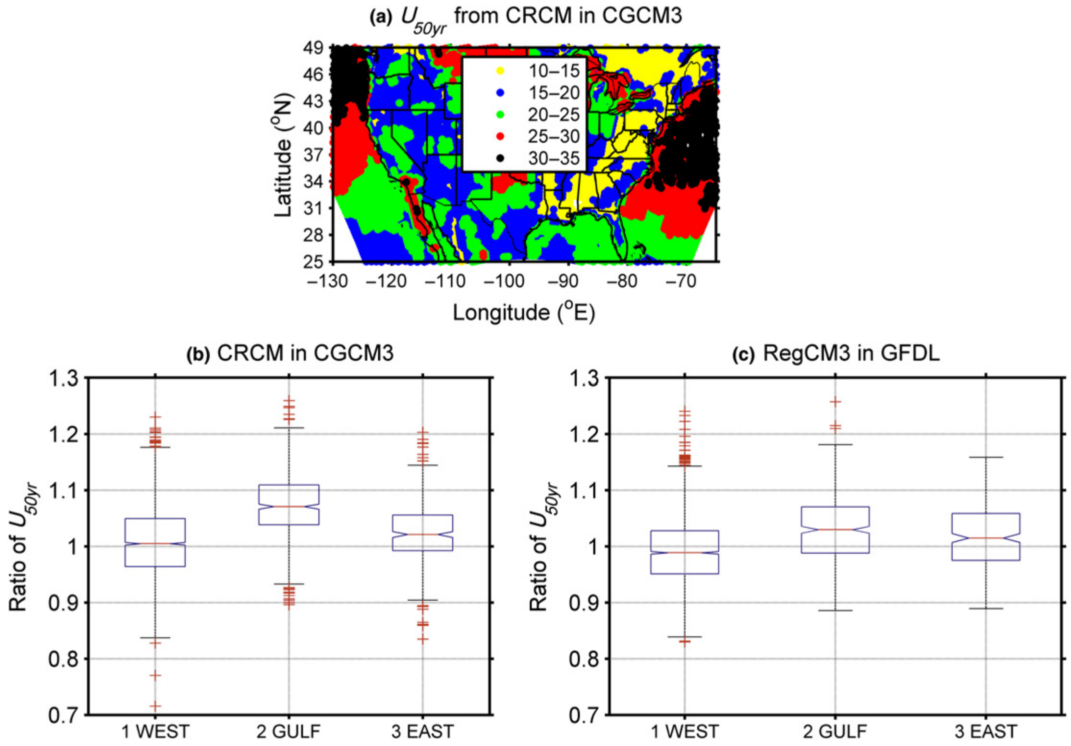

Figure 5 (a) Fifty-year return period sustained wind speed (U_{50yr}) (m s^{-1}) at 10 m over the contiguous USA and surrounding waters during the historical period (1979–2000) derived from output from CRCM nested in the Canadian AOGCM version 3 (CGCM3). The two lower frames show box-plots of the ratio of U_{50yr} (2041–62 versus 1979–2000) in coastal grid cells (i.e., grid cells within 100 km of the coastline) in simulations from (b) RegCM3 nested in the Geophysical Fluid Dynamics Laboratory (CM2.1) AOGCM and (c) CRCM nested in the CGCM3. The regions denoted in frame (b) and (c) are as in **Figure 3**. These simulations were conducted under the NARCCAP, and the future period assumes greenhouse gas emissions according to the A2 A1B emission scenario.

A similar analysis of possible changes in U_{50yr} was conducted using the same NARCCAP RCM simulations as described above for the wind resource. When the results of those calculations are conditionally sampled to select only offshore grid cells within 100 km of the US coast, and U_{50yr} estimates for 2041–62 are compared to 1979–2000, the results indicate a weak tendency toward increased extreme wind speeds, although most grid cells show <20% change in absolute magnitude of extreme wind speed (Figure 5).

These analyses of extreme wind speeds derived using output from RCMs thus may be taken to indicate little change in extreme wind loading. However, there are some important caveats that should be applied to these sorts of analyses: The current formulations of RCMs and the application at approximately a 50 km grid-spacing (as in the NARCCAP simulations) preclude treatment of phenomena, such as severe thunderstorms and/or coastal jets that may be associated with damaging winds and high structural loading. Thus further work is warranted to both identify the sources of extreme loading and evaluate the ability to simulate those phenomena in both the current and the possible future climate states, particularly for combined wind–wave loading.

The IEC 61400-1 standard for wind turbine design prescribes a range of additional extreme wind load design cases including extreme operating gust (Revfeim and Hessell 1984; Mitsuta and Tsukamoto 1989; Kristensen et al. 1991), the extreme wind direction change (Dekker and Pierik 1999), the extreme wind shear, and the extreme coherent gust with direction change (Larsen and Hansen 2008). Simulating the physical causes of such events is extremely challenging and quantifying possible changes in these phenomena in the context of climate change represents an even greater challenge to climate science. It is possible that changes in thermal regimes as a results of global climate change may alter the frequency and/or characteristics of mesoscale phenomena such as low-level jets (Smedman et al. 1996; Wu and Raman 1997) and roll vortices (Etling and Brown 1993) that are experienced in the coastal zone. Such changes could considerably impact the local wind resource and/or wind speed profiles and/or extreme wind shear or gusts, but such effects are difficult to quantify and have yet to be given the warranted attention.

Beyond the midlatitudes even less research has been conducted to examine possible changes in ocean technology resources and/or operating conditions as a result of global climate change. In tropical regions, the frequency, duration, intensity, and track for tropical cyclones have a profound impact on the extreme wind and wave climates and energy transfer in the entire global atmosphere. Controversy surrounds identification and quantification of historical and possible future variability and tendencies in tropical cyclone statistics (Weisse and von Storch 2010). Some analyses report evidence for historical increases in Atlantic tropical cyclone and hurricane activity (Emanuel 2005), while others emphasize the high inter-annual variability and resolve no clear tendency in future scenarios of frequency and intensity (Villarini et al. 2011). Thus there appears to be little consensus currently regarding historical tendencies or likely future tropical cyclone climates.

Loading on wind turbines located offshore is a function not only of the wind conditions but also parameters like sea depth and bathymetry, which affect wave height and type (Bergdahl et al. 2007), and/or the action of sea ice (Clausen et al. 2007). Thus the IEC standard 61400-3 for offshore wind turbine has additional requirements for evaluation of external conditions at offshore wind energy sites (Saigal et al. 2007). However, the wind–wave coupling makes it hard to assess possible climate change impacts. Currently the IEC standards conservatively assume that the extreme mean wind and the extreme sea state occur in the same storm system and thus seek to capture the worst-case scenario.

As a first approximation the fatigue wave loading on offshore structures (expressed as a force per unit length on a cylinder) may be computed using Morison's equation as (Burrows et al. 1997; Wolfram 1999)

$$F = \frac{\rho_w}{2} D C_D |u_w| u_w + 0.25 \rho_w \pi D^2 C_M a \qquad [11]$$

where

C_M is the inertial coefficient (∼2) (Veldkamp and van der Tempel 2005)

C_D is the drag coefficient, given by $C_D = \sqrt{\frac{8\sigma_{u_w}}{\pi}}$

D is the diameter of the tubular element (turbine foundation)

u_w is the wave-particle velocity orthogonal to the axis of the tubular element

a is the wave-particle acceleration orthogonal to the axis of the tubular element

ρ_w is the water density

σ_{uw} is the standard deviation of the wave-particle velocity

From the above equation, it can be seen that faster moving, larger amplitude waves exert the greatest force and hence load on wind turbines deployed offshore. However, detailed estimation of sea state and loads are significantly more complex and nonlinear modifications are likely necessary for improved accuracy (Veldkamp and van der Tempel 2005) particularly of joint wind and wave loading (Ditlevsen 2002; Tarp-Johanssen 2005). Further, uncertainty remains particularly regarding extreme wave loading in shallow water depths where the current generation of offshore turbines is deployed. As relatively high waves run into shallower water (Gravesen et al. 2005)(Christensen et al. 2007) (i.e., at about $H/d > 0.3$) the wave shape distorts (van der Temple 2009) and ultimately the wave will break (at approximately $H/d = 0.78$). The breaking wave load can be approximated using (van der Temple 2009):

$$F = \frac{\rho_w}{2} C_s A u_w \qquad [12]$$

where

A is the area exposed to the breaking wave

C_s is the slamming coefficient (approximate range 2–6.3)

Full treatment of combined wind–wave loading remains incomplete, but innovative solutions to reducing the probably of structural failure of offshore wind turbines due to wind and wave loading are being vigorously pursued and include tuned liquid column dampers (Colwell and Basu 2009) or modification of the support structure construction materials (van der Temple 2009).

WEC are potentially even more sensitive to possible changes in extreme wave conditions than wind turbines deployed offshore. Indeed, the two primary design and cost considerations for WEC are the need to generate energy at competitive economic rates in average sea states and the need for the WEC to ensure survivability in extreme storm (and wave) conditions (Westphalen et al. 2009; Van Paepegem et al. 2011). Given the importance of the overall cost of engineering the device to withstand extremes, over-engineering can render the WEC uncompetitive, while the converse can lead to catastrophic failure.

Sea ice and particularly drifting sea ice potentially greatly enhances wind turbine foundation loading and would also pose a substantial threat to wave energy devices. For example, the drift speed of ice floes can exceed 1 m s^{-1} in some parts of the Baltic Sea and can cause high loads and severe vibration problems on offshore structures (Karna and Kolari 2004; Barker et al. 2005; Gravesen et al. 2005). Ice cones (Yan et al. 2006) have been deployed on some turbines within this region to reduce the ice forces acting on the structure by a factor of 5–10 (Vølund 2005), though they do add to the size of the structure at water level, which may enhance wave loading. There is some evidence for historical decreases in ice cover in both the Baltic Sea and the Great Lakes and speculation for continuation of those tendencies in the future (Pryor and Barthelmie 2012a), though the implications for wind and wave energy extraction technologies remain somewhat unclear.

Icing on wind turbines derived from atmospheric deposition also represents a major challenge to installation and operation of wind turbines (Hochart et al. 2008) and even modest accumulation of ice substantially reduces electrical power production (Laakso et al. 2003; Dalili et al. 2009), although proven solutions to preventing and reducing icing exist (Hochart et al. 2008). Given the complexity of the processes involved in icing (Pryor and Barthelmie 2012b), the potential impact of climate nonstationarity on the frequency or intensity of icing in specific locations is uncertain.

3.04.4 Concluding Remarks

Tremendous energy is available in the form of winds, waves, and tidal currents, and technologies exist that allow electricity generation from the kinetic energy within these fluid motions. As described herein, the precise magnitude of the resources is variable dependent on assumptions regarding accessibility, and technological and societal constraints, but according to many assessments the technological feasible electricity generation potential may exceed current global demand. Of these resources offshore wind energy has greatest market penetration, but technologies to harness wave and tidal currents are proven.

Changes in local and regional climatology may change the context in which ocean energy technologies are deployed and operated. Herein we have presented a brief summary of the current status of efforts to harness these resources, and an analysis of the key parameters that exhibit both relevance to the renewable energy resources and potential climate change sensitivity. Changes in climate may alter either the resource magnitude or operating conditions for the ocean energy technologies, but research in these fields is relatively nascent. Research conducted to date has focused principally on offshore wind energy and indicates that at least in the regions that have experienced greatest deployment to date, climate change projections do not indicate substantial changes in the resource magnitude or loading conditions in the near-to-medium term.

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3.05 Biomass

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3.05.1 Introduction

Biomass has been used as a fuel source ever since humanity learned to make fire. Biomass served as the primary source of energy—before fossil fuels became common in the twentieth century—and still remains the dominant source of energy for one billion of the poorest people (Nature News 2008). Biofuels are attractive for number of reasons. Plants act as 'solar panels' converting the incoming solar radiation to accessible energy, capture carbon dioxide from the atmosphere, and store energy.

Plants are considered inefficient 'solar panel' since they utilize only 1% of the sun's energy (Nature News 2008). The energy content of the biomass represents 95 TW constant energy flux (Miyamoto 1997). Energy is often discussed in energy amount terms expressed in J, ToE, or kWh with an implicit per year dimension which practically leads to energy flux; therefore, this chapter discusses energy uniformly as energy flux expressed in watts. Applying the 10% rule of ecology, which states that only 10% energy is transferred from one trophic level to another (and the remaining 90% is used to support the organisms' own metabolism), reduces further the biofuels' solar utilization efficiency (the ratio of the energy produced versus solar energy reaching the earth surface) to 0.1%. Furthermore, biofuel production (growing feedstocks, harvesting, and processing) adds an additional 'trophic level' that has its own 'metabolisms' taking up as much 66–90% of the energy produced. The energy requirement to produce biofuels are often characterized as the ratio (*r*) of the energy output–input. Optimistic estimates for r are in the 1.3–1.5 range (Giampietro et al. 1997; Shapouri et al. 2003). These ratios can be converted to the energy investment content as $\mathrm{Ce} = 1/r \ {*}100\%$ that yields $\mathrm{C^e} = 66.6-77\%$ which is remarkably similar to the ecosystems metabolism. Therefore, the resulting solar utilization efficiency intuitively could be as low as 0.01–0.03%.

Biofuels are still attractive because they solve the equally challenging problem of portable energy storage. Liquid fuels as portable energy have no real alternatives in many applications such as transportation, field equipments, etc. Interestingly early pioneers of automobiles Henry Ford and Rudolf C. K. Diesel saw biofuels as the fuel of the future.

In recent years, developed countries invested heavy in biofuels as a supplement to fossil fuels. For instance, the United States ramped up its biofuel productions. In 2007, 20% of the grains produced in the United States were used to make biofuels contributing less than 1% of the national fuel consumption (Pimentel 2009a). Unintended consequence of the increased biofuel productions was a rapid increase in food prices (Oxfam International 2008).

The climate vulnerability of biofuel productions is not any different from the vulnerabilities in food productions discussed extensively in other sections of this encyclopedia. A more fundamental question is, if biofuels could be considered as a major contributor to a decarbonized global economy.

3.05.2 Rationale for Biofuels

With the exception of geothermal energy, all renewable energy sources rely on the sun as the primary energy source, therefore they can be judged by considering their solar utilization efficiency. As a baseline to evaluate this efficiency, one should consider the ratio of the energy demand versus the available solar radiation. The Earth's surface (land and oceans combined) receives 95 PW solar energy (absorbs 89 PW and reflects 7 PW), but only ~30% is land, which receives ~27 PW (28%) solar insolation, since the average solar radiation hitting the Earth is slightly higher over ocean ($197\,\mathrm{W\,m^{-2}}$) than on land ($183\,\mathrm{W\,m^{-2}}$) (Jacobson and Delucchi 2011). Twenty-one percent of the continental land is not suitable for crop production; therefore, the solar utilization efficiency is around 0.45%, which already accounts for the plants metabolism. Hence the actual solar energy efficiency of the plants is 4.5%, which is much better than the 1% according to Nature News (2008).

It is also remarkable that the real solar utilization efficiency of the most efficient solar panels are very similar. Although 20–30% efficiency is reported for concentrated solar panels, but that is the efficiency of the panel itself, while the mirror reflecting the sun's radiation typically only covering 25% of the land. Photovoltaic panels (with up to 10% efficiency) when

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installed with spacing are also likely to be under 5% solar utilization efficiency. Apparently, plants by no means are less efficient than solar panels. Based on the 0.45% theoretical solar utilization efficiency (after discounting for the plants metabolism), the net solar utilization efficiency is 0.045–0.15% (after adjusting for the energy demand of the biofuel production), which is somewhat better than our initial crude estimate (0.01–0.03%).

The solar energy available for biofuel production is less than the 79% that is suitable for biomass. Eleven percent of the continental land already used to grow crops and 9% is occupied by human infrastructures (Pimentel and Wilson 2004), that leaves only 59% of the land mass receiving ∼16 PW the solar energy available for energy production. The global energy use passed 16 TW in 2010 after a small drop for the first time in 2009, which is expected to grow (one has to note that all scientific papers (e.g., Pacala and Socolow 2004; Delucchi and Jacobson 2011) demonstrating possible pathways to decarbonized global economy that rely only on renewable sources (and exclude nuclear power) assume that global energy use can be lowered below contemporary levels and ignore more realistic IPCC energy demand projections anticipating substantial economic growth in the developing world) ∼28–60 TW (Grübler et al. 1996; Nakicenovic et al. 2000); therefore, the demand and solar power supply ratio today is ∼0.1% that will grow to 0.2–0.4%, which is far less plentiful than advocated and it is higher than the net solar utilization efficiency (0.045–0.15%) calculated above.

The low 95 TW energy available from biomass contrasted with the global energy use alone should be alarming, regarding the feasibility of biofuels as major source of energy, since it indicates that that a large share of the biomass will need to be utilized. At the 0.045–0.15% rate, biofuels could produce 7.2–24 TW net energy from the 16 PW reaching the available 59% of the continental land. Therefore, biofuels by no means could be or should be considered as a major source of renewable energy. The only reason biofuels might remain attractive is the recognition of the need for energy storage.

The energy density of fossil and biofuels exceeds the energy density of other viable means of storing energy, e.g., electric batteries, flywheels, pumped storage, etc. Furthermore, recharging batteries is slow compared to refueling. The slow recharging is not a technological challenge, but constrained by fundamental physics. The energy content of a 40 l fuel tank in a mid-sized passenger car is about 1320 MJ. To transfer that amount of energy in a 1–2 min refueling stop would require 220 kV at 50 A or 50 000 A at 220 V electric currents (i.e., the equivalent of the maximum electric load of 1000 homes using regular a 50 A circuit breaker). Even if electric vehicles take over some part of the ground transportation, battery powered aviation and other long distance transportation (that have no access to power lines continuously) seem to be infeasible.

Transportation takes up 20% (3 TW) of the global energy use today that varies by countries (e.g., 28% in the United States). Even if the energy demand to grow crops was satisfied from other sources (providing the 'metabolism' of the biofuel productions from external sources), producing transportation fuels from biomass for today's consumption would require the utilization of 3% of the continental plant biomass, which would need to double or triple.

These calculations are crude estimates that could have been made 20+ years ago. The following sections will be testing these rough estimation with real biofuel statistics and more comprehensive modeling studies.

3.05.3 Sources of Biofuels

Direct biomass combustion is the most efficient way of utilizing the plants energy that could be as high as 45% (IEA 2007), next to gasification of the solid biomass. Fuel shortage during World War II in Europe has led to the conversion of the majority of vehicles to firewood (http://www.lowtechmagazine.com/2010/01/wood-gas-cars.html) (Figure 1).

The gasification (burning the wood with low oxygen) has a 60–70% efficiency producing wood gas (a mix of hydrogen and carbon monoxide) that is combustible by both gasoline and diesel engines. Despite its relative efficiency, large scale adaptation of solid biomass as a transportation fuel is very unlikely and liquid or gas biofuels are likely to remain the preferred choice, unless other means of portable energy storage emerges.

Biofuels are normally characterized as conventional or first generation biofuels, second generation or cellulosic biofuels and next or third generation biofuels from algae. First generation biofuels only use some parts of the plants that contain sugar, starch or some form of oil that could be either fermented to some form of alcohol (e.g., ethanol) or converted to biodiesel. Second generation biofuels utilize the entire plant by breaking up cellulose to small sugar compounds that is ultimately fermented to alcohol. The next or third generation of biofuels is produced by algae under heavily controlled environment, where carbon dioxides are supplemented along with key nutrients.

3.05.3.1 Traditional Biofuels

The most efficient biofuels today are made from sugarcane. Sugarcane is a water intensive crop, which grows all year around in tropical climate. Brazil, the largest producer of ethanol, grows 73.8 t of sugarcane per hectare (Goldemberg 2008) that yields up to 9000 l ethanol (Brown (2006) gives a much more modest 2500 l ha^{-1} estimate that is below sugar beets). Considering the energy density of ethanol (24 MJ l^{-1}) and the solar radiation all year around, the solar utilization efficiency is 0.37% (less than our 0.45% rough estimate without adjusting for the energy needed to grow, harvest, and process the sugarcane to produce ethanol).

Sugarcane is by far the most efficient crop in terms of return on energy investment (Brown 2006). The 1:8 ratio (one unit of energy yielding eight times more energy) means that the production efficiency is 87.5% and only 12.5% energy is lost to support the production's 'metabolism.' Part of this high efficiency comes from using the rest of the sugarcane as solid fuel resource. Due to the high efficiency of the ethanol production from sugarcane, the net solar utilization efficiency is 0.315%, which is higher than the current energy use solar radiation ratio and will remain even in the future, with elevated energy demand.

The second most efficient biofuel crop is sugar beet, which could yield 2700 l ethanol per hectare (Brown 2006), that is

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Figure 1 Wood gas car from WWII era.

0.11% solar utilization efficiency one-fourth of our crude estimate. Sugar beet has 1.9 units of energy output for one unit investment (which is 47.3% production efficiency), so the net solar utilization efficiency is 0.051%, significantly below sugarcane. The relatively high production efficiency cancels out the lower than expected solar utilization efficiency; so the resulting net solar utilization efficiency is in the same ballpark as our crude estimate.

Corn ethanol is the third most efficient biofuel that yields 1350 l ethanol per hectare. The solar utilization efficiency therefore is 0.06% (significantly below our initial 0.45% estimate). The energy return of corn ethanol is heavily disputed. Some authors argued that the net energy return is either miniscule or negative after factoring in the energy cost of growing crops and processing into biofuel (Giampietro et al. 1997; Pimentel 2009b). Other authors demonstrated that the energy investment return ratio is positive and could be as high as 1.5 (Brown 2006). The more realistic consensus value is 1.25 (Hill et al. 2006; Farrell et al. 2006), which leads to 20% production efficiency. The dominant portion of the extra 25% comes from accounting for the energy content of the by-products, without that, the energy content of the produced ethanol and invested energy are almost the same (Hill et al. 2006). The net solar conversion efficiency is a very low 0.01% (below our initial 0.045% estimate).

Critiques, who defended corn as viable source of biofuel, apparently addressed the wrong side of the equation. Corn clearly passed the point where it can be considered as any energy source, but it may remain as a viable means of producing liquid fuel. At 0.06% solar conversion efficiency 18% of the continental lands (receiving 27 PW solar energy) would be needed to satisfy the 3 TW liquid fuel need of the transportation today.

Biodiesels represent another class of biofuels derived from oily plant products (e.g., palm oil, coconut, rapeseed, peanut, sunflower, and soybeans). Biodiesels have 38% higher energy content (33 MJ l^{-1}) than ethanol, but most of the plants producing them have lower yields. Only palm oil and coconut (which can only grow in the tropic) have comparable yields 1900 and 870 l ha^{-1}, respectively (Brown 2006). Those plants that grow in temperate climate have lower yields (Brown 2006) between 211 l ha^{-1} (soybean) and 380 l ha^{-1} (rapeseed) resulting in 0.05–0.10% solar utilization efficiency for tropical crops and 0.01–0.02% for temperate crops (well below our crude estimate). These are very low numbers, way below our crude 0.45% figure, regardless of the energy needed for producing them. While the energy investment return ratio of the soybeans are as high as 1.93 (Hill et al. 2006), it does not help in offsetting the poor overall solar energy conversion efficiency.

3.05.3.2 Second Generation Biofuels

Second generation biofuels convert cellulose to liquid fuel allowing the utilization of the entire plant that is made up dominantly by cellulose. Despite its appeal, cellulosic biofuels are still in the experimental stage and commercially viable solutions that are ready for large scale adaptation are anticipated to require another decade of research and development (Schnoor et al. 2008). The main challenge of the cellulosic biofuels is the efficiency of the cellulose conversion. While enzymes can convert sugar to ethanol with 90% efficiency, converting cellulose to ethanol has only 40% efficiency (Service 2010), because the cellulose needs to be broken up first. As a result, converting plant biomass to ethanol requires processing much larger amounts of feed stock to produce the same amount of biofuel than conventional biofuels. Temperate zone plant biomass per hectare could be as high as 20 t. Switchgrass have reported yields up to 30 t ha^{-1}. The most efficient cellulose conversion yields 180 l ethanol from 1 t of feed stock (Badger 2002) resulting in 3600–5400 l ha^{-1}, that would represent 0.31% solar utilization efficiency. The 180 l t^{-1} might be an optimistic productivity that largely depends on the efficiency of the cellulose to sugar conversion that could be as low as 76 l t^{-1} and has a theoretical limit at 350 l t^{-1} (Badger 2002). If truly realized, the 0.31% solar utilization efficiency would approach sugarcane.

Melillo et al. (2009) arrived at a similar 0.26% solar utilization efficiency modeling the production of 10.2–11.6 TW energy (anticipated to cover the energy needs for transportation by 2100) over 14–15% (20.6–21.6×10^6 km^2) of the continental land with a Terrestrial Ecosystem Model (Melillo et al. 1993). While the authors of this study discuss the impact of such land use change on carbon emission, they do not mention the consequences of appropriating additional 14–15% land for biofuel production (without actual energy gain).

One has to recognize that the 0.31% solar utilization efficiency is largely an optimistic estimate that is not yet supported by real world data. Commercially operational systems are still lagging, because conventional biofuels are still less expensive to meet the government dictated biofuel contribution (Service 2010). It is certainly alarming that cost competitiveness of the cellulosic biofuels remains behind traditional biofuels.

3.05.3.3 Third Generation Biofuels

A third class of the traditional biofuels (besides ethanol and biodiesels from terrestrial plant) is the biodiesel from algae. Microalgae is largely promoted as the truly viable means of biofuel production. Interestingly, the literature discussing terrestrial crops are rather quiet about the production rates per unit area, while the microalgae literature emphasizes heavily the much improved land use efficiency. The reported 98 400 l ha^{-1}

bio-diesels yield (Chisti 2008) is indeed impressive and represents a remarkable 5.4% solar utilization efficiency. At this level, plants are comparable to solar panels. If realized, microalgae could compete not only as liquid fuel, but as an energy source with regular solar panels.

While the theoretical yields of microalgae are indeed promising, the reality is that these yields could be achieved only in the tropics and subtropics and require significant infrastructure. The open pond systems have far less efficiency and the high yields are achieved only in 'closed' system, where the microalgae grown on plastic tubes constantly feed with CO_2 and various nutrients, while the produced O_2 is degassed regularly. These facilities are more akin to incubators than agricultural fields, and the high solar utilization efficiency comes from significantly reducing the energy needs of the microalgae to maintain their own metabolism. In other words, the microalgae are spoon fed to the degree that almost all of the energy they consume goes into producing biomass.

3.05.4 Biofuels and Climate

Growing feed stocks for biofuel productions has similar climate vulnerabilities and impacts on the climate system as food production. The primary difference is the degree to which intensive agricultural practices, that tend to need more energy, can be applied for energy crops. In other words, if the additional energy invested in the crop production can be justified in terms of the energy return from growing more crops.

Given the poor solar utilization efficiency of biofuels demonstrated in the previous section, satisfying liquid fuel demands via biofuels will require substantial land conversion. Growing plants for biofuel will inevitably lead to competition with either food production or ecosystem preservations. Proponents of cellulosic biofuels often emphasize that the feeds stock to produce cellulose can be grown on marginal lands that are not suitable for food crops, but they forget to realize that those 'marginal' lands are often the last sanctuaries for wildlife.

3.05.4.1 Climate Impacts

Land cover conversions affect the climate a number of ways. The change in albedo alters the energy budget, while the changes in the plants' physiology and phenology modify the water budget. Plant characteristics (e.g., canopy height, rooting depth, leaf area index, etc.) affect land surface properties. The climate impact depends on vegetation that is replaced and the plants that are grown instead (Pielke et al., 2007). Land conversion from forest or tall grass to annual crops is reported to increase albedo and decrease water uptake, while replacing short grass could decrease albedo particularly outside of the growing season (Beltrán-Przekurat et al. 2011).

Land conversion to expand first generation biofuels productions will have the same climate impacts as traditional food crops, since their feed stock comes from similar plants. Second generation biofuels utilizing plants that are closer to native vegetation will lead to a return to land-cover conditions closer to natural conditions. Georgescu et al. (2011) analyzed the impact of converting annual crops to perennial switchgrass in the United States and concluded that such conversion would lead to a regional cooling, due to increased evaporations combined with higher albedo throughout the entire year, which is just the opposite that occurred when tall grass vegetation was converted into croplands.

Land conversion for biofuel production can increase greenhouse gas emission (Searchinger et al. 2008) through emission due to land-use change. Melillo et al. (2009) argued that proper agricultural practices (particularly in terms of sensible fertilizer use) combined with protecting forested lands could reduce greenhouse gas emissions dramatically.

3.05.4.2 Climate Vulnerabilities

First generation biofuels likely have the similar climate vulnerabilities to traditional food crops, since they are not fundamentally different. If second generation biofuels will ever become a reality, their feed stocks will likely be more resilient for several reasons. Firstly, second generation biofuel crops will be closer to natural vegetation that adopted to particular climate conditions (e.g., switchgrass or managed forests). They have demonstrated resiliency surviving in marginal lands. These perennial plants will grow continuously, as the weather conditions permit, without elevated sensitivities during particular phases of their phenology (e.g., early plant growth or around harvesting) as a consequence, harvesting could be aligned better to periods when the harvesting is convenient, as opposed to being dictated by the crops' maturity.

3.05.5 Summary

The solar utilization efficiency of the biomass is clearly below the ratio of energy demand and the available solar energy, which by itself should have ruled out biofuels as viable renewable energy source. With the exception of sugarcane and microalgae (if it becomes scalable reality), biofuels are not efficient enough to become major sources of energy. Various forms of biomass should be utilized whenever they are available as a supplemental energy source, but plants are not efficient enough to capture solar energy.

The only rational for biofuels is if there is no alternative to produce similar portable form of energy. Even if the energy to produce biofuels is produced elsewhere, and biofuel only serves to provide liquid fuels, the land requirements are still huge. While satisfying liquid fuel demands using biofuels is possible, the environmental costs and competition with other land uses (particularly food production) probably will be prohibitive.

Sacrificing 14+% of land just to produce biofuel (while the actual energy still needs to be produced elsewhere) will clearly introduce competition for land. Biofuel advocates are very keen in claiming that their feed stock will not compete with food production, but the reality is, the 14+% expansion will either come from lands that could grow food or lands that was left for natural ecosystems. Lands dedicated to biofuel feed stocks are not likely to allow rich biodiversity, particularly the frequently disturbed monocultures. Managed forests might offer better compromise between biofuel production, while allowing healthy ecosystems to thrive for a decade or two between harvesting.

Perhaps, part of the reason why the high land requirement was not admitted as a major obstacle is that using 14+% of the land is not impossible, but clearly destructive either to food production or to natural ecosystems. It is hard to understand why renowned Nobel Prize laureate economist, Paul Krugman, is more willing to blame the weather (http://krugman.blogs.nytimes.com/2011/02/05/soaring-food-prices) for the soaring food prices than recognizing the obvious causality between the cost of food and burning food crops for use in gasoline.

If all the corn produced in the United States were diverted for ethanol production, it would only contribute 12% to its demand (Hill et al. 2006). In a world, where every seventh (925 million) person is still hungry (FAO 2010), burning food crops to substitute for a tiny fraction of the fuel demand is unethical. From the taxpayers perspectives, donating subsidized agricultural products to feed the hungry would have just as little or no benefit as burning it in cars, but at least it would support a noble cause.

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3.06 Vulnerability of Solar Energy Resources under Climate Variability

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3.06.1 Introduction

An economy based on solar energy has been the dream of many for many years. It would be great to depend only on the freely distributed energy of the sun, which is available everywhere. Doing so might diminish geopolitical concerns and environmental impacts. However, the current reality is quite different. While energy from the Sun is free, it is very difficult to collect it, concentrate it, convert it, move it, and store it. You could say that nature has developed a great way to accomplish these tasks for us – converting the products of biological photosynthesis into oil and concentrating it in geologic reservoirs in a liquid form with high-energy content that allows easy transport and storage. However, that process required millions of years to build up resources we are using up at an increasing rate; it would be nice to develop our own way of accomplishing this in a way that is economically and environmentally feasible.

This chapter first looks at the important role that energy plays in society. It has been one of the main drivers in the organization of civilization and, before that, in evolution. The availability of relatively inexpensive energy could solve many other problems, for example supplying fresh water through desalination.

While solar energy might include a wide range of potential energy sources, including the previously trapped solar energy in fossil fuels, the indirect renewable solar energy of wind and waves, and the natural direct way of growing biofuels, the solar energy considered here is restricted to solar concentrators, solar photovoltaics (PVs), and artificial solar chemical processes. After we consider these, we explore both the related uncertainties and the possible range of climate variability. Then characteristics of the various technologies, uncertainties, and potential climate effects are identified. An analysis explores the solar energy technologies, uncertainties, and vulnerabilities related to climate.

Finally, an integrated analysis method of real options analysis (ROA) provides a potential semiquantitative framework for discussion and interpretation. The purpose of this chapter is not to address the potential impact of using these renewable resources on the consequences or probability of climate variability; this has already been addressed in a wide variety of reports (IPCC 2011).

3.06.2 Energy Is Key

Previous studies have suggested that technology, energy, and societal changes are coupled, perhaps in a long-term learning pattern (Marchetti 1980; LePoire 2010a). Major changes in energy sources and in the intensity of energy use in this sequence seem to coincide with some transitions in international leadership (i.e., when a nation-state overtakes a previous leader). The current struggle to supply expanding energy demands to a global economy will also be likely to use new technologies, such as nanotechnology, biotechnology, information technology, and cognitive science (NBIC) for new energy sources, conversion, storage, and transmission (Roco and Bainbridge 2002). While the United States currently leads the way in the development of many high-level technologies, other countries, such as China, are indicating their interest in these technologies through their internal research and development (R&D) investments (Lacey 2011). The use of new technologies in energy production is important to understanding leadership transitions, since it has been suggested that a major factor determining whether societies transform to more complex forms is their ability to increase the intensity of energy use. To gain a wider perspective, the historic roles of energy, technological, and leadership development are reviewed within a possible logistic growth and transition framework.

White (1959) was one of the first to make the connection between energy and cultural change. He identified the leverage that technology could provide to sustain more complex societies. This work was incorporated into the analysis of the collapse of complex agricultural societies by Tainter (1988, 1996), who identified the marginal return on investment of resources, such as energy, as societies grow larger and more complex. He

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suggested that many agricultural societies collapsed because they overextended their reach into nonsustainable systems. The impact of environmental degradation has also been an important factor in the development and decline of civilizations (Ponting 2007; Chase-Dunn and Hall 1997; Diamond 2005). Most analyses focused on agricultural societies because of their simplicity relative to industrialized societies.

Chaisson (2001, 2004) recently connected the flow of energy (i.e., the free energy density flow) to possible bifurcation points throughout the history of the universe, from galaxy formation to present society. However, Chaisson's focus was on connecting the early development of galaxies, stars, and planets to the period of time since the Big Bang. Therefore, graphs of the progression of energy flow over time display recent acceleration.

A slightly different point of view is obtained if energy use comparisons are made based on times before the present. They show a geometric increase in energy use through biological, cultural, and technological evolution with logarithmic time (LePoire 2010b). The connection between increased energy flow and historical transitions was also suggested by Prigogine (2000) and Spier (2010).

Richard Smalley of Rice University, the 1996 Nobel Prize winner in chemistry for the discovery of fullerenes in the mid-1980s, offered a possible way to tie these transitions together and hopefully take advantage of their benefits while managing, or at least reducing, possible risks. He suggested that the United States should lead an international effort to explore the possibilities of using nanotechnology in the energy sector. He argued that energy is the key to many international problems, such as the water crisis, food availability, environmental deterioration, poverty, terrorism and war, disease, education, democracy, and population sustainability (Smalley 2003).

How might nanotechnology be applied to the energy problem? Smalley identifies a set of technologies, from cheaper and more efficient production of PVs to dye-sensitized coated nanoparticles forming Graetzel cells. Storage and transmission issues can also be addressed with technologies that facilitate photoconversion of water to hydrogen, better fuel cells, better hydrogen storage, and more efficient power cables. Additional resources facilitate new research communication, linking ideas with market opportunities, and comparison of global strategies. The U.S. Department of Energy shares research discoveries of the Advanced Research Projects Agency – Energy (ARPA – E) through conferences (U.S. Department of Energy 2011a) and energy innovation portals (http://techportal.eere.energy.gov) with webinars.

Another model of technological progression and diffusion is based on the logistic equation. This progression assumes that the rate of progress is proportional to both the current level of complexity and the fraction of complexity yet to be discovered. Modis (2002) suggests that the history of the universe might best be viewed as a logistic development of complexity. He arranged important events in the history of the universe from a variety of sources, assumed that each event was equally important, and then made the assumption that the complexity of an event is its importance divided by the transition time to the next event. The dependence of the cumulative fraction of complexity on milestone number (not the event's time) could be interpreted either as the first half of a logistic curve or a sequence of events that will culminate in a singularity. A logistical development of complexity would mean that the rate of development depends on the product of the cumulative complexity of previous events and the fraction of complexity is yet to be discovered. Modis favored the logistical development interpretation.

Logistical trends in the world's mix of primary energy sources were observed (Marchetti 1977) in the mid-1970s. The analysis was based on an extension of the Fisher–Pry (Fisher and Pry 1970) model for substitution. The model accounted for the shifts in primary energy use from the early 1700s, where wood was the primary source of energy, through the 1800s, where coal use climbed, through the early part of the twentieth century, where oil became predominant and uses of natural gas and nuclear power rose. The logistical trends were extended to predict the fall of the fraction of energy from coal, the peak in the fractional use of oil, and the continued rise of both natural gas and nuclear power in the 1990s.

However, the actual use of primary energy sources during this period has shown deviations from these predictions, in that the relative fractions of the primary energy sources seem to have been somewhat stable since 1990 (Kulcinski 2004). During this period, total energy demand substantially rose, but the contributions from each primary energy source kept pace. While it was recently suggested (Smil 2000) that the logistical analysis of primary energy sources might not be appropriate for predicting long-term energy use, perhaps an extended substitution model including efficiency could help explain these trends. A large factor in energy use dynamics in this recent period was substitution of conservation and efficiency for actual use (Ausubel 1996). A simple measure of the world's energy efficiency over this period can be constructed based on energy intensity (i.e., the measure of gross national product per unit of energy use) and incorporated into the logistical model. With this extension, the logistical model is more consistent with historical data, including the current trends (LePoire 2004) (Figure 1). This suggests that energy efficiency (or conservation) might be viewed as a viable alternative when considering energy use. Some see the possibility of greater efficiency in energy use (Ayres et al. 2007). If the 'efficiency' wave follows a substitution path similar to that of coal and fluid fossil fuels (oil and natural gas), a new wave would be expected to follow. The transitions to alternative energies have come in slower discrete steps, first through the development of hydropower dams, then through nuclear power. If alternative energy sources continue to follow the efficiency wave, they are expected to be comparable to the energy derived from fossil fuels after 2050.

3.06.3 Energy Scope

The amount of solar energy absorbed by the Earth is large compared to the current consumption of energy. The amount of energy absorbed in 1 h is equivalent to the annual total energy used around the world. A small fraction of this energy is converted into wind (0.06%) and slightly more is converted by photosynthesis into biomass (0.077%). The amount of solar energy absorbed by the Earth in only half a year would

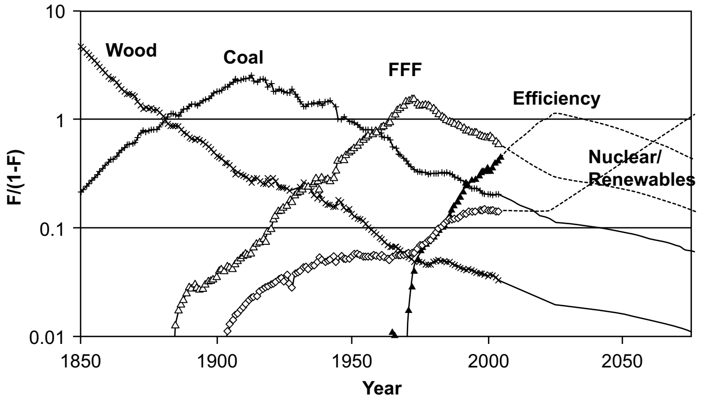

Figure 1 Logistical trends of world energy use extended in time with projected data from the International Energy Outlook of the U.S. Department of Energy's Energy Information Administration. The *y* axis shows the ratio of the fraction (F) from a fuel source to the fraction (1-F) from other sources. The transitions follow from wood, coal, fluid fossil fuels (FFF, i.e., oil and natural gas), efficiency, and then a growing fraction of nuclear and renewables. The historical analysis includes the energy saved through efficiency (and conservation) as measured by considering the energy use to gross domestic product (GDP) ratio. The projections are based on continued logistical substitution.

be equivalent to the total amount of nonrenewable energy that exists in the form of fossil fuels and uranium.

This chapter covers PVs, concentrating on thermal solar power and engineered chemical conversion. It does not include biofuel production, even though distinguishing between these may become increasingly difficult as natural biological and engineered systems are merged (e.g., genetic engineering of plants and use of algae in process systems). We do not consider indirect solar energy such as the conversion of heat differences into wind and waves. Another type of indirect solar energy is generated by hydropower dams, which rely on the sun evaporating water for later collection at higher altitudes. Large-scale hydropower energy generation is quite efficient and has limited environmental impacts near the dam; however, many of these locations have already been developed, leaving limited growth opportunities for smaller installations. Solar heating of housing spaces and water is very important but is considered part of energy efficiency in building design. Classification by passive, active, and indirect technologies is shown in Figure 2. This is just suggestive because the boundaries between these categories are often blurred.

Solar energy depends on infrastructure, most specifically on that related to the transmission and storage of energy. If the requirements are not met, for example if solar energy is only

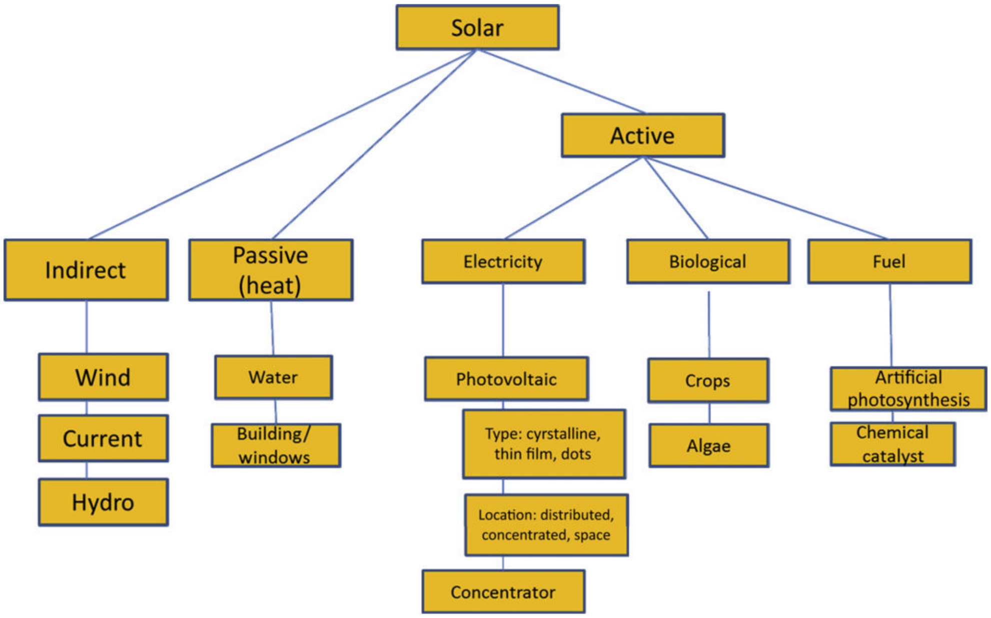

Figure 2 Organization of some solar energy sources by passive (e.g., buildings, water heaters), indirect (wind, current, hydropower, and ocean thermal), or active. The active part includes growing biofuels. More emphasis in this analysis is given to active generation of electricity or catalyzed fuel. Electricity can be generated through solar concentrators using heat engines or the use of PVs.

available during clear sunny days, then requirements for supplemental energy production (e.g., gas turbines) are needed. Integration into the grid may require long transmission lines and better pricing (smart grids) (Solar 2011).

Techcast (Halal 2008; Halal and Huhn 2012) polls experts about the future prospects of technological development. The current poll on alternative energies, including nuclear and renewables (biomass, hydropower, wind, and solar), suggests that 30% of energy will be globally supplied by alternative energies in 2023 (±5 years). This is somewhat in line with the projections of various governmental agencies, such as the U.S. Department of Energy (DOE) projection of 28% by 2036, the California and Hawaii goals of 20% by 2020, and the European Union goal of 22% by 2020. Currently, about 18% of energy is globally supplied by alternative energies (i.e., 82% of energy is fossil based). This includes the 6% nuclear and 12% renewable, the latter of which is dominated by hydropower (6%) and biomass (4%) such as wood. Only 2% comes from wind and solar energy, and the majority of that is wind energy. However, the growth rate for solar energy has been spectacular (although it started from a very small value), growing by about 60% per year from 2006 to 2011 (i.e., a factor of 10 in this time frame). However, in 2011 there was an oversupply of solar panels, resulting in a projection of only about 10% growth in the next few years. The cost of solar panels dropped from about \$1.75 W^{-1} to about \$1.10 in 2011. This panel cost is usually only about half of the installed cost; the rest of the cost comes from power electronics (10%) and installation, along with balance-of-system costs (40%).

A recent exploration of possible scenarios was conducted (Lovins and the Rocky Mountain Institute 2011). These scenarios included business as usual, a slow migration to alternative energies, and a transformation of the energy sector through breakthrough efficiency and renewable development.

The DOE Sunshot Initiative has been promoting a goal of less than \$1 W^{-1} of installed capacity by 2017 (U.S. Department of Energy 2010). It looks at the three potential candidates for solar PV: crystalline silicon, thin film, and concentrated PVs. A recent workshop identified the potential costs savings leading to this goal. A major target is the expense of installing the panels. The panels must be protected from the worst types of weather, so designs incorporating different material and inexpensive shock absorbers are being studied. This is crucial for considering the effect of potentially more violent storms in areas where the panels might be installed. Further exploration is being conducted to reduce the thermal response to the system and improve efficiency, installation costs, and overall lifetime.

Each solar technology has environmental impacts (U.S. Department of Energy 2011b). A common impact is the use of a large area, although the area might already be in use (roofs) or in remote locations (deserts). Production material impacts vary among the technologies, including glass and polymer for concentrators, semiconductors for light conversion, rare earth elements for the transparent layer of PVs, and a host of catalysts for chemical conversion. Operating material impacts include the water requirements for operating thermal engines or for keeping the surfaces clean. Further resources are needed for transmission, storage, and base-load backup. Another measure of impact is the energy return on investment, measuring the energy required to make, operate, and dispose of the energy producer over its lifetime. These measures of material and energy use are often captured in a lifecycle analysis.

Total lifecycle costs are needed to identify the main determinants of lifetime, maintenance, and improvements to extend life. This is especially true for solar because the fuel is free and the main cost is the initial capital cost. Extended over the lifetime, these costs really determine whether solar energy is cost effective or not (Humphries 2011). Besides total lifecycle costs of the specific installation, solar technology and its commercialized production is still rapidly developing. There are many uncertainties and potential paths yet to be explored that will determine the final portfolio of potential options, such as land requirements, integration into the electricity grid, resource requirements, and overall costs.

A major resource requirement for capturing the diffuse energy of sunlight is the land on which to place the solar collectors. Location depends on the availability of good sunlight, good connection to the grid, and sufficient land, as well as being able to easily construct and maintain the facilities. Various locations include distributed houses and business rooftops (German), deserts, oceans, Earth orbits, and the moon. The Energy Realities Web site offers many information resources, including a map of solar irradiance. Many of the world's deserts can be identified with the highest irradiance (**Figure 3**).

A summary of some solar technologies including a short description, current use, possible projection, and examples of research and development actions is listed in **Table 1**. The concentrator and PV are still being researched, but large-scale deployments are also being made, so these technologies are more mature and known. The artificial photosynthesis technology is newer and has not been commercially deployed, but it aims for a market which others have difficulty filling (i.e., production of high-energy density fuels for transportation).

An alternative to using fuels for transportation would be to convert transportation systems to run on electricity or convert electricity to fuels for use in transportation. However, these would require larger investments in infrastructure to support them. Since there is already an infrastructure for liquid fuels, the more direct production would facilitate conversion of transportation to solar power. A brief description of this artificial photosynthesis research follows. Two longer-term extensions of PVs are the ability to collect a broader range of frequencies and to overcome the limiting day–night cycle of terrestrial installations. These two extensions are also briefly summarized.

Biomimicry was employed in Nocera's 25-year quest for scalable solar energy solutions (Nocera 2009). In their search for creating artificial photosynthesis, his team at Massachusetts Institute of Technology recently identified two natural biological techniques that had previously remained hidden. He noticed that some life forms use cobalt in photosynthesis. He then developed a long-lived cobalt-based catalyst that uses sunlight to convert water into oxygen and hydrogen gas. This work supports his goal of finding a chemical process that could be distributed (e.g., on houses) and robust (e.g., not decay) in converting sunlight into liquid chemicals (e.g., alcohols) that store energy for later use in transportation as a gasoline substitute, or as electricity with a fuel cell. His team's recent discoveries have led to a start-up company, Sun Catalytix, that is partially funded by the US government's ARPA – E program, which funds selected promising energy-related innovations. In

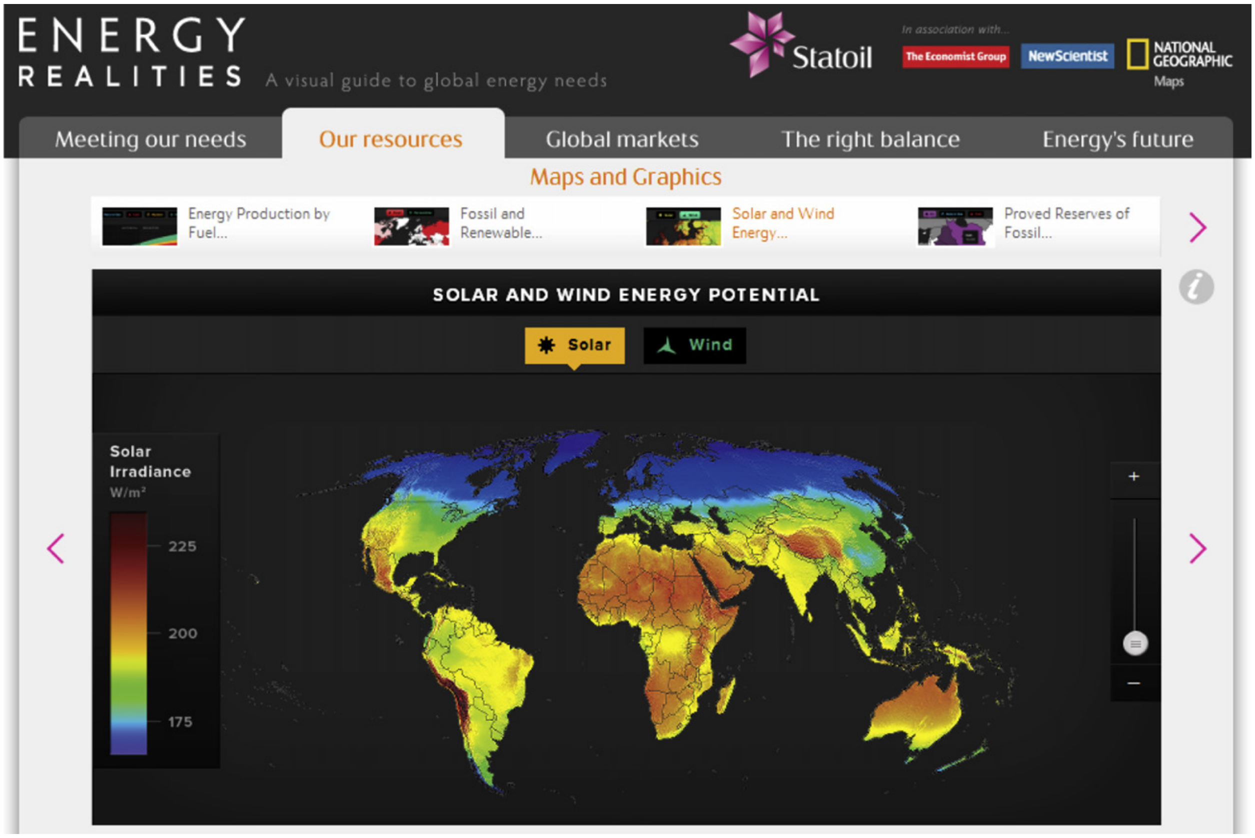
ENERGY REALITIES
A visual guide to global energy needs
Statoil
In association with...
The Economist Group
NewScientist
NATIONAL GEOGRAPHIC Maps
Meeting our needs
Our resources
Global markets
The right balance
Energy's future
Maps and Graphics
Energy Production by Fuel...
Fossil and Renewable...
Solar and Wind Energy...
Proved Reserves of Fossil...
SOLAR AND WIND ENERGY POTENTIAL
Solar
Wind
Solar Irradiance
W/m²
225
200
175
+
−

Figure 3 Web sites such as Energy Realities offer information resources regarding the energy situation and opportunities. This particular snapshot shows solar energy potential based on solar irradiance. Many of the world's deserts show up tinted orange. The sparcity of sunlight in Canada, northern Europe, and Russia is visible. [Available online at http://www.energyrealities.org/our-resources/solar-and-wind-energy-potential/erp64A8DF68B7E76DA07.]

the lab, it seems like the catalyst also works in impure water, which could lead to it being used not only to generate and store solar energy but also to purify water. Lewis at Caltech is also searching for artificial photosynthesis in a different way, by using nanotubes along with a membrane to generate hydrogen from light (Lewis 2012).

The use of nanotechnology might lead to designs that more efficiently convert energy. Two examples can be found in the fields of solar and nuclear energy. In the solar area, conventional solar cells use silicon cells doped with special elements. Visible light strikes a cell, causing an electron to jump into a conducting zone. The electrons are then collected as electricity. The interaction of light with the electrons might not be efficient as a result of other energy transfer mechanisms, such as the light creating heat or the electron losing the energy before contributing to the current.

However, sunlight includes more than just the light we see. Much of the energy from the sun is infrared light that we cannot directly see but we can experience as heat. Infrared light is also generated when the visible light from the sun heats the earth. This energy can be reradiated into the sky, contributing to the cooler, clear, cloudless nights. A solar cell that could extract this infrared energy would be able to provide energy both day and night (although not as much at night). However, the infrared light does not have enough energy to kick the electrons to their conduction zone.

Another way to extract energy from the light is to use an antenna, much like a radio or cell phone antenna (Stricker). This method of collecting solar energy has advantages, in that an antenna is more efficient at capturing the energy, absorbs at a wider range of angles than conventional cells, and does not require exotic materials to make. However, the antenna has to be about the same size as the wavelength of the light. For radios, this is about 1 m. For cell phones, it is a few inches. For short-wavelength infrared light, the wavelength is about 1/25 of the width of a human hair.

One antenna would not only be difficult enough to make, but it would also result in very little energy production. The challenge was to easily produce millions of these small antennas, which was successfully done at Idaho National Laboratory (a DOE facility) along with other laboratories; the work received the 2007 Nano50 award. The laboratories were able to 'print' 250 million metal antennas on plastic about the size of a standard sheet of paper. However, converting the absorbed energy (10 GHz frequency) into useful electricity (60 Hz frequency) remains a problem. This conversion typically requires the use of diodes that allow the flow of electricity in only one direction. The University of Colorado at Boulder is currently making progress in developing the necessary diodes.

The idea of solar space-based energy extraction has been around for decades. Obstacles include the high price of sending reliable equipment into space, maintaining it there, and the

Table 1 Brief summaries of some solar power technologies. Organization into direct and indirect capture is shown in **Figure 1**. Characteristics include a brief description, current and possible projections, and example R&D actions

Solar energy technology	*Brief description*	*Current and projected use*	*Example R&D actions*
Solar thermal water heating	Mostly distributed residential and commercial installations to heat and store water for local use	154 GW China (plan on 210 GW by 2020), true potential scenario (420 GW by 2015), and 1500 GW by 2050)	Reducing cost and extending ease of connection
Concentrated solar	Mirrors focus light onto a centralized tower; parabolic troughs focus on a tube; or dishes that have a central focus on Stirling engine	1 GW (2010), 1.5 GW (under construction), 6 GW (contracted); Spain, United States, Algeria (Desertec (Hickman 2011))	Reduce cost of mirror, replace glass with polymer, increase efficiency, mass production
Photovoltaic	Doped semiconductor, either in crystalline or in thin film form; solar light energizes electrons to conduct electricity; some systems enhance collection with concentrating lenses	Capacity of over 60 GW by the end of 2011 Lovins (Lovins and the Rocky Mountain Institute 2011) 2050 scenarios (in units of installed capacity/% of electrical energy use): ● Maintain: 200 GW/10% ● Renew: 500 GW/30% ● Transform: 1000 GW/40% Most in the form of utility-scale plants	Use of quantum dots or multilayer films to capture a broader set of wavelengths; some materials require rare earth elements (Humphries 2011); some materials are environmentally hazardous and might be released during production or after use, but this could be mitigated by developing a recycling initiative (Knight 2010)
Solar chemical	Captures solar light with molecules and converts the energy into chemical bonds; sometimes similar to artificial photosynthesis; a large advantage is that liquid fuel potentially could be generated for transportation; the fuel also acts as a high-energy-density storage medium	Currently only research projects	Mimic nature with the use of cobalt-based compounds; take advantage of catalysis such as found in complex nanostructure materials
Biofuels	Crops are grown and converted to a liquid fuel such as diesel or ethanol; a disadvantage is the large amount of energy input required to grow the crops with fertilizers, transportation, and conversion; another drawback is the economic competition of the crops for both fuel and energy	Lovins (Lovins and the Rocky Mountain Institute 2011) 2050 scenarios (in units of % of electrical energy use): ● Maintain: 3% level ● Renew: increase to about 20% by 2030 while solar grows and replaces ● Transform: 6% peak	Ability to convert inedible parts of plants such as cellulose; ability to convert parts of inedible crops that grow on land that do not compete with food crops; decrease the cost to convert the crop mass into fuel
Hydropower	Elevated water from solar evaporation to drive turbines near a dam; most large dam sites have already been developed but some smaller sites remain; currently one of the largest (and oldest) of the renewable energy sources	Currently about 6% of energy Not much change is expected	Optimize energy extraction from rivers with minimal ecological disruption
Wind	Wind turbines generate electricity; the wind is generated by thermal spatial differences	Lovins (Lovins and the Rocky Mountain Institute 2011) 2050 scenarios (in units of installed capacity/% of electrical energy use): ● Maintain: 200 GW/8% ● Renew: 500 GW/30% ● Transform: 1000 GW/40%	Ability to connect into the grid; determination of lifetime costs; feasibility of offshore windfarms
Passive Buildings	Orientation, active screening, and thermal masses optimize the use of passive solar irradiation	Lovins (Lovins and the Rocky Mountain Institute 2011) estimates that in 2050 buildings might use half the energy, but this includes all forms of smart controls and efficient technologies, not just passive solar	Design integrated systems; use new materials and smart controllers to gain advantage

uncertainties associated with transmitting the energy back to the Earth (Landis 1990; Rouge 2007). Two locations are currently being explored. One is a geosynchronous orbit location. Satellites with very large solar collection arrays could be placed in geosynchronous orbit to continually collect energy from the sun at a fixed location above the Earth's equator. The benefits of this location include the lack of clouds or night interruptions and the fact that there is no need for a wide expanse of land for collecting the energy. However, the power must be collected and sent back to Earth. The original designs included microwave transmission from the satellites to an Earth-based rectenna. This system could reliably and efficiently transmit the energy to Earth, where it would be converted back to electricity and placed on the grid. In the 1970s, estimates for the system were made and compared with data on other technologies. At the time, the cost was found to be prohibitive. Japan is currently making an investment to look into this technology's near-term development (Richard 2009).

The other space location being explored is the moon, which offers the advantages of allowing the use of existing materials and providing a more conventional work environment. The available materials would, of course, have to undergo extensive processing to support the energy collection, electrical conduction, and conversion needed for microwave transmission. This would take quite a bit of effort, and current human space flight and work is expensive and difficult. A Japanese company (Corporation) is exploring the use of semiautonomous robots to do the primary conversion of materials and build the solar energy collection system. The idea is to create a continuous strip of land, perhaps going all the way around the moon's equator, of solar cell collectors built with moon materials. A complete equatorial ring would allow continuous energy collection. The sun shines only half the time on the far side of the moon, yet the same side of the moon is always facing the Earth, so just a limited number of transmitters would be needed.

To make this plan more feasible, space travel and the movement of materials need to be more economical. There have been several attempts to improve the space elevator concept, which was first proposed by the Russian scientist Tsiolkovsky in 1895 (Edwards and Bradley 2003; NOVA 2007). A major obstacle is the strength of the material needed for the spine of the elevator, which must reach over 24 000 miles from the geosynchronous orbit down to near the Earth level. Recently, the National Aeronautics and Space Administration (NASA) and Edwards have been updating the design on the basis of the idea that carbon nanotubes, which have the necessary strength, can be scaled up to provide enough material and consistency for the long cable.

3.06.4 Uncertainty Scope

There are different types of uncertainties (Figure 4). Many deal with the unknowns of the future (i.e., the results of research, the political responses, and the world economic situation). These future states of technology, political will, and economics are

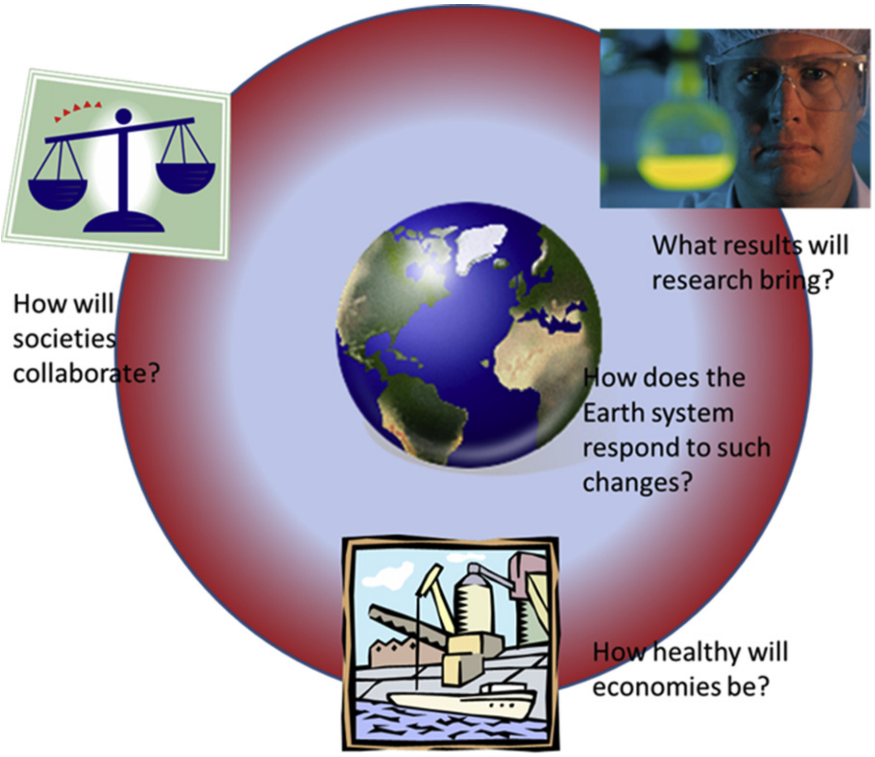
How will societies collaborate?
What results will research bring?
How does the Earth system respond to such changes?
How healthy will economies be?

Figure 4 Sources of uncertainty in this issue. A central issue is our incomplete understanding of how the Earth system works, including the atmosphere, oceans, and ecosystems. Understanding this would help determine the relative costs of energy impacts and assess the potential limitations on development. Three issues shown on the outer rim signify uncertainty about the future: the results of research, the response of societies and states, and the state of the economy. These are major factors in determining costs and feasibilities of energy deployment.

embedded in a world that is facing many environmental limitations (Fiksel 2010). One response is to explore sustainable paths with renewable energies. However, this transition would take place within the context of other difficult transitions such as changing demographics, population pressures, and diffusion of technologies. One goal is to navigate these issues to a path that increases a sustainable quality of life around the world. A series of questions concerning uncertainties is presented in Table 2.

One uncertainty that is not tied to the future is exactly how the earth system would respond to various activities by humans. The environment system is not understood well enough to predict the results of atmospheric emissions or land development. This uncertainty is being tackled by improving models, collecting and interpreting measurements, and developing analogies. One difficulty in understanding such a complex system is its ability to support a wide variety of positive and negative feedback loops. Positive feedback (e.g., loss of reflective ice through warming causing additional heating through absorption) can result in nonlinear responses and discrete, perhaps irreversible, shifts to other system states. Some analogies that have been developed are often controversial and sometimes conflicting, such as the Panarchy (Gunderson and Holling 2002) model initially derived for isolated ecosystems, the Gaia Hypothesis (Lovelock 2006) that explores ways the Earth establishes a dynamic equilibrium, and the Medea Hypothesis (Ward 2009) that explores how the Earth system seemed to crash causing mass extinctions of life forms.

The social and political response uncertainties include the ability to collectively make decisions, the ability to finance large operations, and the incentives given to make changes. These tough problems, labeled as wicked problems by Conklin (2006), have characteristics that include a larger number of stakeholders or groups, goals irreducible to simple monetary measurements, large amounts of uncertainty, and potential nonlinearity, which makes them difficult to predict. The process of handling them requires decision under uncertainty with conflicting perspectives and interpretation, and the ability to alter the course after more is known. While these elements of uncertainty, guesswork, and conflicting opinions, and midcourse adjustments are often seen as a weak decision, this closely resembles the scientific process.

One aspect of economic uncertainty is the relative cost of energy as the transition from fossil fuel takes place. Currently, there is wide interest in natural gas exploration and development with new techniques. This might beneficially impact the

Table 2 Questions that arise concerning the identified four factors of uncertainty with this issue. Again, many questions belong in more than one category

Uncertainty component	*Contributions*
Earth system	How does reducing fossil fuel aerosols affect climate?
	How will polar ice and water levels change?
	How will fresh water and regional climate be affected?
	How much stored methane will be released from ocean clathrates and permafrost?
	How quickly would the Earth naturally restore processes?
	How effective would geoengineering strategies be?
Society collaboration	Will distributed (individuals and states) solutions be identified or will international collaboration be necessary?
	Will sustainable incentives be found to effectively integrate change into the economic system?
	How will blame be assigned and handled?
	Would large centralized solar facilities be targets for terrorists?
Economic health	Will other alternatives be identified (e.g., inexpensive disruptive energy sources)?
	Will renewable energies be relatively less expensive than current energy prices?
	What role will energy play in curbing demand?
	How fast will other countries develop toward the energy intensity of the current developed world?
	Will the future quality of life depend on the current levels of energy intensity in the developed world?
	Will substitutes be found for liquid fuel for transportation?
	How much capital investment and relief will be needed to deal with the environmental disasters and failing states caused by any climate variability?
	Will the prime location of centralized solar power, the deserts, be politically stable?
	Will these uncertainties be reduced enough to encourage the long-term financial commitments necessary for the capital-intensive solar projects?
	What will be the maintenance costs of the projects?
	What relative merits will there be for centralized versus decentralized systems?
	Will smart metering lead to much improved economical use of energy?
	How translatable will the systems be to various parts of the globe?
	Will space costs be reduced to consider space deployment?
Research and development	Will the research subsidies be enough to find a solution to overcome the technological lock-in problem?
	Will the lifecycle costs of the technologies be reduced enough?
	How long will the research and manufacturing learning curves continue?
	Where will the weak link be in the system of energy collection, conversion, storage, and transmission?
	Will the research be dispersed and later focused effectively?
	Will the full environmental impacts be anticipated or will there be surprises?
	What level of renewables will be supported with a limited smart grid?
	Will storage systems, such as hydrostorage and batteries be developed in time?
	If fossil fuel base backup is needed, how much gain in emissions and costs is realized?

transition – through maintaining a relatively smaller carbon emission than coal along with a reasonable price – or be detrimental to the transition by diminishing the incentive to change and invest. As impacts become clearer, the relative bearing of the externality burden from wastes, such as carbon dioxide, will be revisited. The corresponding incentives and taxes will affect the relative cost of the renewable energy. The cost of energy will also have an impact on the relative cost of trade, with higher costs tending to move production to more local sites. The continued global development will affect the energy demand. A quick growth would lead to increased energy growth, although with perhaps more energy-efficient methods. A world with the same energy per capita use as the United States would require the world energy output to increase by a factor of about four.

Research uncertainties are very large in this case; there is little actual deployment and the learning curve is still showing large reductions. The current research covers a very broad range of potential technologies (U.S. Department of Energy 2011a), which probably will be pruned as conclusions regarding development and deployment are reached. Technological surprises might also occur, similar to the discovery of power by nuclear fission in the 1940s. Many researchers are exploring a host of ways to mimic the sun by controlling fusion in terrestrial power plants, but the goal has been elusive; new problems arise as soon as others are resolved. For example, it is known that stable heavy negatively charged particles could catalyze fusion in water very simply, as demonstrated by the (not so stable) catalysis of muons. Progress in the infrastructure is also needed, but large storage batteries are difficult to construct. Sometimes the technology seems close but elusive; for example, the discovery of higher temperature superconductors in the 1980s seemed to offer the possibility of more efficient transmission lines, but both understanding the science and developing the technology have been difficult. Besides the research on actual conversion, change will occur in both energy and material efficiency as lifecycle costs and environmental impacts are considered.

Large uncertainty generates both risks and rewards. For large deployment projects, investors are concerned about the uncertainty of the price, lifetime, and potential displacing alternatives. This is also seen in the nuclear energy sector, where large capital investments are important. Rewards go to the investors who see the opportunity in innovative companies that combine technology, pricing, and opportunities at the right time. Various countries are viewing various renewable energy and infrastructure opportunities with different incentives for attracting investors (Pew Charitable Trusts 2010).

3.06.5 Climate Effects Scope

Climate variability might have a large impact on many systems. The direct effects are those from changes in the weather, which can cause effects that ripple throughout a very complex system with social and technological implications (Figure 5). The boundaries of the effects on this system are difficult to define, especially since the use of solar power might create a feedback cycle by impacting the consequence and probability of climate variability. Some summary descriptions of examples in these areas are listed in Table 3.

The direct effects are changes in the weather such as temperature, storm intensity, average cloudiness, sea level changes, more drought in some regions, and more floods in other regions. These changes would influence where people live and where agriculture might be sustained.

Indirect effects are based on the difference of direct effects on potential substitutes or competing needs. For example, there might be a greater demand for nonenergy-related water supply and land demands might change for food or biofuel crops. In addition, responses might include an indirect effect of pricing consequence through taxes such as a carbon tax.

If the climate variability is large, infrastructure for mitigating the direct effects, such as improved coastal water management, might compete with the need for improved energy transmission and storage. For renewables like solar power, if sufficient storage capability is not established, then backup base-load stations will also have to be a part of the system. These base-load systems might be more directly affected by climate.

Finally, there are the large effects caused by the ways climate influences societal decision making. Will individuals have the right incentives (e.g., a fair price for energy, including the full impact of the lifecycle of fuel extraction and wastes)? Will collective actions be found? Will perceptions of unfairness in the assignment of fault contributing to climate variability result in international sanctions against countries not cooperating? Will geoengineering be explored?

The impact of climate on solar energy depends both on the level of change in the climate and on the fraction of energy eventually supplied by solar systems. If the relative amount of solar energy remains small, there is little impact. However, dependence on a large fraction of energy from solar plants would increase the sensitivity to many factors such as water, land, and finance.

The lifecycle costs of low-intensity renewable technologies and their environmental impacts on land (McDonald et al. 2009) have yet to be determined.

3.06.6 Analysis

Some general requirements for solar power are access to the sun and, since the raw energy source is free, the capital and land necessary to capture, convert, store, and transmit the energy. The amount of sun that falls on a particular area is affected by the latitude, cloud cover, season, and interfering structures. Near-term climate variability is expected to cause average storm tracks to move northward, leaving higher average sunlight levels to the south (United States Global Change Research Program 2009). Unfortunately, the two requirements of availability and infrastructure costs seem to be opposed. For example, the best place to capture unimpeded solar energy would be in space, but the transmission and material transport costs would be large. The capacity for land to generate solar power is often indicated by arid deserts such as the US Southwest and the African Sahara Desert. Unfortunately, these are also the indications of low population density, and would also require large material transfer and transmission in difficult environments. Important potential impacts are listed in Table 4.

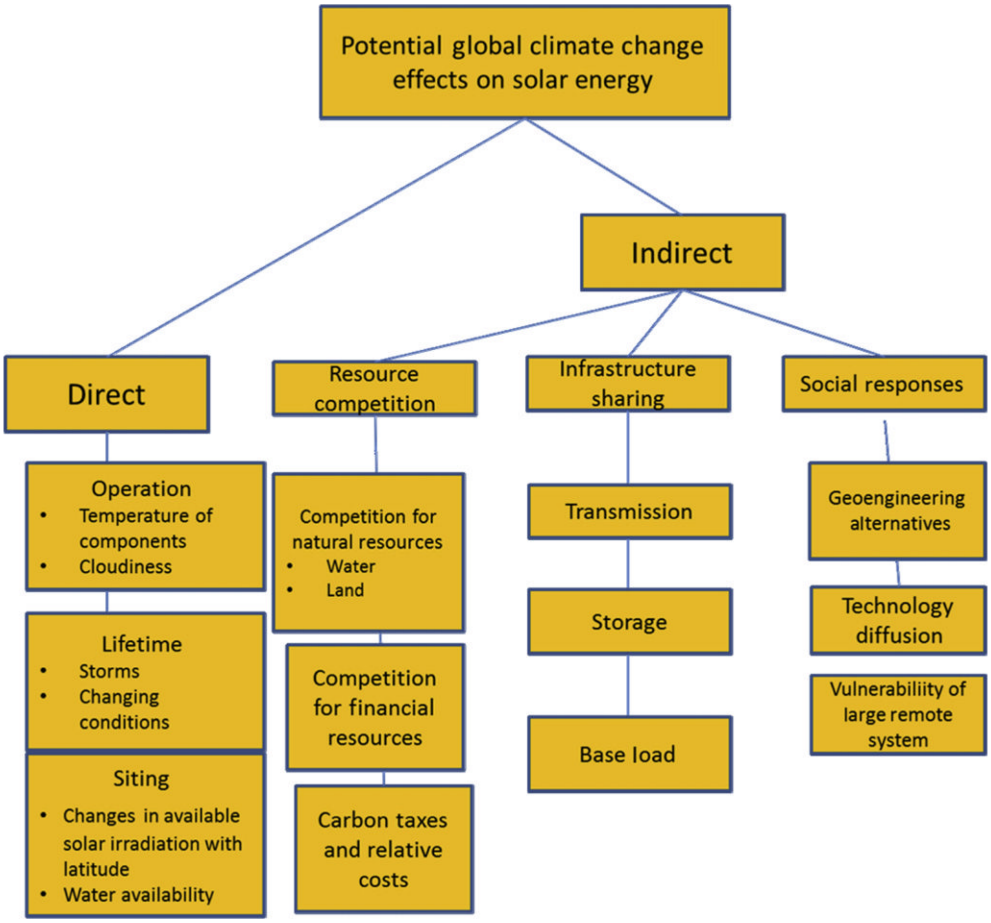
Potential global climate change effects on solar energy
Indirect
Direct
Resource competition
Infrastructure sharing
Social responses
Operation
Temperature of components
Cloudiness
Lifetime
Storms
Changing conditions
Siting
Changes in available solar irradiation with latitude
Water availability
Competition for natural resources
Water
Land
Competition for financial resources
Carbon taxes and relative costs
Transmission
Storage
Base load
Geoengineering alternatives
Technology diffusion
Vulnerabiliity of large remote system

Figure 5 A conceptual categorization of potential global climate change effects on solar energy development. These include direct effects of weather changes on operation, lifetime, and citing. Indirect effects include resource competition, infrastructure development, and potential social responses.

The best case would be something like geospatial orbit where the installation could be in full sunlight 24 h a day without clouds or interfering structures. A problem arises however, when the energy has to be sent down to Earth. Microwaves or space elevators have been proposed to accomplish this, although the technology to accomplish these seems to be in the far future, requiring the cost of space transport to be reduced.

3.06.6.1 Capacity

The Rocky Mountain Initiative has developed a strategy called ‘reinventing fire’ that looks at additional energy efficiency in transportation, buildings, and manufacturing. They all looked at three different energy scenarios of demand and supply. In their business as usual scenario, things get quite a bit worse with price increases being mitigated by increasing energy efficiency only. In their mixed portfolio scenario, there is less pressure but still large uncertainty in providing the energy at a reasonable value. In the advanced energy scenario, alternative renewable sources (wind and solar but not traditional hydropower) supply 30% of energy by 2025. The solar part of this is expected to be 10% of the energy supply with an energy growth factor of 1.5 between 2010 and 2030. This would mean that 2 TWh of power would need to be generated per year. At a 20% collection efficiency, this would mean using an area of 4000 square miles.

Some major factors hindering the current use of solar power are its relative cost, the lack of an infrastructure to support renewable energy, and uncertainty in committing upfront financing while the energy situation is so uncertain (Laitner 2004). One strategy for development is to take advantage of learning curve cost reductions through subsidies and funded research. The dispersed nature of power from sunlight leads to the development of large amounts of land and the development of large complex transmission lines and storage and/or backup systems. While very large-scale growth of solar to the point where it would dominate the energy portfolio is a long way off (e.g., over the 50 years the President’s Council of Advisors on Science and Technology (PCAST) estimated to change the energy system), the more feasible goal of supplying 30% of energy by 2025 does not seem to be hindered by many factors of potential from climate change. One factor that may play a part is the availability of financing, especially if large climate variability happens before the learning curve can achieve cost comparability between solar and other resources. The funding to respond to local efforts, and of developing countries to respond to potential humanitarian efforts, might diminish the financing needed. Other organizations at smaller levels, such as the business group, realize the potential interconnected issues and threats and so are developing their own strategies for possible collaboration.

Table 3 Potential effects of climate on solar energy systems. A categorization of effects as direct or indirect is given in **Figure 4**. While the direct effects of temperature, cloudiness, storm intensity, and water availability will impact some areas, a major effect is caused by the more complex indirect effects such as competition for financing for both the energy collection sites and the corresponding infrastructure. Social responses concerning the ability to develop and maintain the systems are also a factor

Type of effect	*Climate effect*	*Effect on solar energy development*
Direct	Temperature increase	● Effect on water heating beneficial (Bengtsson 2007). ● Solar cell efficiency changes with temperature and can rise above the ambient temperature. ● The change would be different in different places, leaving some places ill-suited for solar energy while increasing the utility at others. ● Water from rain and runoff might change, leading to competition for water. Water is necessary for the thermal engines of concentrating solar and in smaller amounts for washing PVs.
	Cloudiness	● Clouds would obscure sunshine, reducing return.
	Storms	● Large structures are needed to collect the dispersed sunlight energy. The structures need to be capable to withstand the most intense storms, leading to increased construction and/or maintenance costs. ● Larger fluctuations of temperature or conditions may lead to quicker material degradation, thereby leading to shorter lifetimes.
Indirect competition	Land	● Large amounts of land are needed for the collection of dispersed solar energy. The land might be needed for other purposes such as agriculture or conservation. Some desert land when disturbed might release particulates and organisms that cause diseases.
	Financial resources	● Climate variability might increase demand for large infrastructure projects such as levees and flood control. This might put pressure on financial resources to construct large, capital-intensive renewable projects.
	Externality costs	● With more information coming in on impacts from various wastes, including carbon dioxide, the inclusion of the externality costs of various energy sources might be included (e.g., carbon tax).
Infrastructure sharing	Transmission	● Large-scale systems might occur in deserts far from large populations, requiring long transmission lines. These lines might be more susceptible to severe weather.
	Storage	● Storage is needed to balance the supply of solar energy to the demand. Currently, many small hydropower dams are used. Climate might affect the suitability of these storage systems.
	Base load	● To assure availability of power when renewables might not be producing, backup power systems are needed. Their intermittent starting and stopping might not be energy or environmentally efficient.
Social responses	Geoengineering alternatives	● If it is believed that geoengineering solutions might be less costly and more effective at mitigating climate effects, the incentive to develop and deploy renewables might be diminished.
	Technology diffusion	● The regional types of research and manufacturing might change in response to climate or availability of investments.
	Vulnerability of large remote systems	● Large remote solar power facilities might be more susceptible to disruption through local development or social protest.

Solar cell production costs continue to decrease with a pattern similar to Moore's Law for computer chips (Naam 2011; Greening et al. 2000; Arvizu 2006). The pertinent question is how to support research leading to an initially broad search but then focus on specific beneficial technologies without technological lock-in. The appropriate technology paths have been developed and revised (Edmonds et al. 2000). Various views of this question have been addressed by government agencies (Hanson and Laitner 2006; Hanson et al. 2004), the president's council advisors on science and technology (President's Council of Advisors on Science and Technology (PCAST) 2010), business groups (American Energy Innovation Council 2010), and local decision makers (Green Rhino Energy 2010).

With these considerations, there might not be a need to put a whole new energy capture, conversion, transmission, and storage system together soon. In fact, the PCAST concluded in November 2010 that to fully transform the US energy infrastructure would take about 50 years. Currently, only about 15–20% renewable sources can be integrated into the system without a large number of storage systems or backup energy generation systems. A backup system might be needed when the renewable sources are not active (at night for solar) or when no wind is blowing for turbines. The backup systems might be natural gas turbines, although some locations might use excess coal power ramping, which might be as efficient as running continuously. For storage systems, the main applications are using small hydropower systems to pump water up with excess electricity and let it flow down when it is needed. Compressed air also has a large current potential for storage, although much research is being done to identify scalable battery systems. The current storage amount of such systems varies; about 10% of US electricity, 15% of European electricity, and 20% of Japanese electricity is typically temporarily diverted. Research continues on finding electrical batteries that meet various storage requirements (Dunn et al. 2011).

3.06.6.2 Other Goals

Obstacles to energy development might be helped by considering factors other than just from climate change. Three dimensions identified are economic, national security, and other environmental impacts. In the economy, oil imports

Table 4 Summary of important potential climate effects on solar energy production. Other vulnerabilities are also identified; while not directly tied to climate, the impacts might result in unexpected disruptions in the system

Timescale	*Vulnerabilities to climate effects*
Short term	● Lack of storage on grid. The current system would be able to support about 20% intermittent renewables before the system would fail to keep balance. Hydropower energy storage is currently being used, but other systems for battery storage are being pursued. ● Potential for technological lock-in of a suboptimal system if the R&D is too diffuse or too focused. The market dominance of a suboptimal technology might later limit expansion because of cost or capacity characteristics. ● Competition for finance with other energy projects and investments due to climate variability. With uncertainty so large, perhaps distributed systems might grow first, demonstrating capabilities. The ability to decrease the overall cost, including the installation and customization, is being addressed in the $1/W program.
Medium term	● Technologies might not diffuse as fast if material and production resources are not distributed. This would be especially true with rising transportation fuel costs. ● Large-scale systems need time to be developed and tested. One estimate is about a 50-year time scale to redevelop the US energy infrastructure. ● Large-scale systems might be developed in the desert, which would require weather and social stability to realize long lifetimes and reduce lifecycle costs. ● A technological surprise might disrupt the need for these systems collecting the diffuse solar energy. Currently there is a wide search in many countries for alternatives such as a more compact fusion energy source.
Long term	● Global development might continue to require more energy per person. This may lead to alternative places to collect and transmit solar energy, such as in space. This would require a drastic reduction in the cost to put material into space. It would probably require international collaboration on a scale larger than the ITER (International Thermonuclear Experimental Reactor) fusion reactor. A full deployment would probably have to be broken into purposeful steps, supply niche needs, and demonstrating capabilities (Landis 1990).

distort both the trade payments and political dependency on exporting countries. Often, these countries might be politically adverse with access to a trade chokepoint such as the Straits of Hormuz. Environmentally, there are other impacts from pollutant gases (NO_x from natural gas use and SO_x from coal use), particulates released from fossil fuel burning, uncertainties about water-energy needs, and nuclear waste.

By looking at the energy problem from multiple goal perspectives, alternative strategies might be discovered (Richter 2011); for example, in the case of the investment in PV solar in California's Million Solar Roofs project, 15% of the cost could reduce as much greenhouse gas as converting an old coal electricity generating plant to use natural gas. In addition, it might foster collaboration between different groups. For example, the American Energy Innovation Council could collaborate with CEOs to form a nongovernmental strategy for energy development.

There is much debate on whether potential climate variability should be considered a national security issue (Matthew 2011). One factor of not acting is the potential opportunity cost of not leading the R&D of new technologies. Other countries, such as China, have already invested quite a bit in developing manufacturing (Lacey 2011). China has quite a bit of investment funding available, while the United States and Europe are considering the impacts of long-term debts. However, not just impacts on each country but potential costs of responding to a series of humanitarian crises might occur if environmental change happens.

3.06.6.3 Research

Many renewable energy technologies depend on discrete energy exchange at the nanoscale levels over very short timescales (Crabtree and Sarrao 2011). Control and understanding of these phenomena require special tools for studying semiconductors, metals, and molecules for capture, conversion, storage, and transmission. Many of these processes are not well understood (e.g., relatively high-temperature superconductors that were discovered about 25 years ago). Often complex materials with small-scale structures or elements control are required to construct these complex materials. New tools such as time-resolved X-ray scattering coupled with detailed computer models are helping determine the path to potential solutions.

An additional problem with research is finding ways to benefit from it with patents while still allowing advances to proceed. There are concerns about recent subsidies and environmental controls at Chinese solar cell manufacturing locations that have recently dominated the production market (Hickman 2011). The financing is interesting because many of the developed countries are experiencing debt crises with concerns over large long-term investment, whereas the Chinese have the largest financial resources to invest.

3.06.7 Methods

Real options analyses facilitate assessment of flexible technology options in quickly changing situations with large uncertainties for actions that might be irreversible. These situations occur in technology-driven decisions where technology, regulations, markets, and scientific understanding quickly evolve (Amram and Kulatilaka 1999). Examples of areas where these conditions often occur are national security, environmental risk management, and applications of advanced technology. Whereas traditional assessments rely on specific alternative actions with few flexible decision points, ROA, an extension of the financial community's options methods, also considers the impact of flexible decisions, such as delaying, switching, expansion, and abandonment, in uncertain conditions, such as fluctuating costs.

The well-known Manhattan Project conducted during World War II is an interesting research case that can be viewed through ROA. The goal was to try to find a way to construct a nuclear explosive device (before the other side did). The most difficult part of the process was to collect enough special isotopic material to form a critical mass. Research showed that there were many potential ways to collect this material (including differential thermal diffusion, magnetic mass separation, gaseous diffusion, and reactor production), but it was unclear which were quicker and more efficient. As a result, many potential options were simultaneously tried. Some methods, after great investments, did not deliver as originally thought. Others were revised as research findings led to reconsideration of the priorities. The great uncertainty and motivation for the research was the threat that the other side (considered between Germany and the United States) would discover the secrets and use the new weapon first. As the war wore on, indications of German research in this area were observed and sabotaged. Near the end, when the decision of deployment was to be made, multiple limited successful special material collection techniques were implemented. Just before the final test of the system, the main motivator was reduced to zero (German surrender without nuclear weapons use).

For example, ROA might be applied to assess portfolios of geoengineering (Lempert and Prosnitz 2011) or renewable energy development options (Siddiqui et al. 2005) to address climate variability. The geoengineering technology options include carbon capture and sequestration, cloud seeding, space-based reflectance, and ocean fertilization. Uncertainties in environmental impacts are aggregated into the uncertain impact cost of carbon emissions (Royal Society 2009). The experience curve model was used for predicting technology development progress. Technology-specific assessments to support this model are being discussed. This model extends previous ROA applications to energy research and environmental technology investment. This technique not only evaluates the research portfolio under uncertainty but also results in intuitive explanations for the various scenario paths. A further benefit can be achieved if the analysis is periodically updated with the actual R&D results and cost fluctuations.

Dynamic analysis can be accomplished through ROA or uncertainty analysis. While 'road maps' are often generated for a technological path, the uncertainty of the technology, collaboration, and impacts would seem to favor a more flexible approach. The approaches might include ROA or parametric uncertainty analysis. These approaches would allow for flexibility but allow qualitative mental models to be constructed and communicated to the public and financial community. The models are capable of accepting new data on the state of the environment, collaboration, and technological research outcomes.

Some requirements for this analysis are constructing a framework of research dependence including serial (i.e., where two branches of research would be used together) and parallel (i.e., where either of two branches of research would be applied). The research would be characterized by parameters such as research costs, the state of uncertainty, potential reduction of uncertainty by research, and potential value of the research outcomes. A large amount of uncertainty resides in the relative costs of fossil fuels, such as oil and natural gas, along with the cost of emission of CO_2 and other greenhouse gases (Figure 6). With ROA, these might be modeled as a lognormal diffusion process. Besides the data on the research and financial environment, decisions rules would have to be made explicit (e.g., research continuation, abandonment, enhancement, and transition to development and deployment). The tool might be used to analyze various research and development incentive policy options, such as collaboration between governments, nongovernment organizations (NGOs), and private industries.

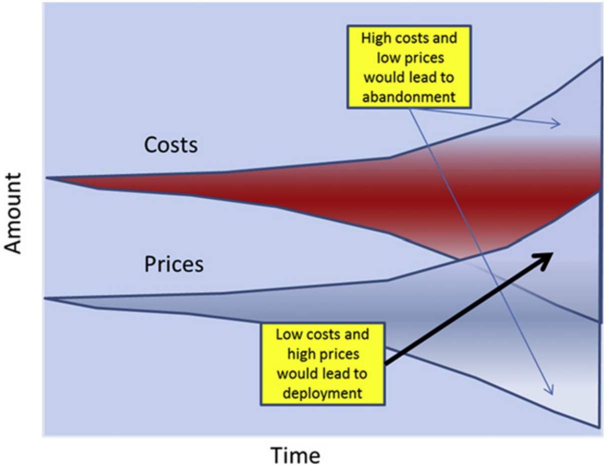
High costs and low prices would lead to abandonment
Costs
Amount
Prices
Low costs and high prices would lead to deployment
Time

Figure 6 Schematic graph of the uncertainty of the costs and prices for the solar energy deployments. Costs are impacted by the results of research, production learning curves, and availability of materials, land, and other resources. The price for the energy is determined by the relative success of competing technologies and demand, which is influenced by energy efficiency levels and global development. Price is also affected by the incorporation of actual costs such as waste (e.g., potential carbon dioxide tax). A real options analysis would reflect these uncertainties along with the learning curves to assess the value for continuing, accelerating, or abandoning certain research and development paths.

There are some trends in aggregate measures of energy use such as the logistic substitution patterns in the fractional use of energy sources over time and the trend in the reduction of the C:H ratio in primary fuels. These trends might provide a bound on the potential scenarios at later times where larger uncertainty arises.

A ROA project would include the following:

- A framework with research estimates. The framework would include sequential and parallel dependencies of research paths and weighted by future contributions based on energy scenarios.
- A ROA for this framework, focusing the uncertainty in the fossil fuel costs with the CO_2 costs folded in.
- Information about data needs for a detailed model (e.g., technology options and uncertainties include potential costs, environmental impacts, and likelihood).
- Dynamic criteria and rules for the dynamic decision options.

It is hoped that the project would demonstrate the benefits of the dynamic decision support tool for research. It should increase confidence in the overall strategic approach to the research investments by allowing for the uncertainties and relationships of the processes to be accounted for and communicated.

Consider that case with two potential competing technologies, each with a different learning curve. The price of carbon might increase or decrease from an initial price, diverging in time. The cumulative R&D costs increases with time, for example through a fixed annual budget. An option might be to fund a small amount of research on one technology resulting in a relatively high unit cost, or much research could be done on the other technology resulting in a relatively lower final cost. If the final state involves small climate variability consequences, then the first technology might be effective. If the final state involves large climate variability, the second technology might be preferred.

Learning curves (or experience curves) have been studied for about 75 years, starting with the observation that as more planes were built, learning-by-doing occurred, leading to lower production costs. The concept is that as more of an innovation is produced, the cost gets lower. The empirical pattern is that a doubling of the aggregate production results in a nearly constant fractional decrease in the costs. However, this can lead to the potential market failure of technological lock-in, since only early technologies, not necessarily the best, would tend toward lower costs and market dominance. Understanding the learning curve and potential costs savings and advantages of technologies leads to estimates of the investment (often governmental subsidy) necessary to encourage effectiveness in the long run (Alberth 2008). Learning curves were used in an integrated energy model of Gritsevskyi and Nakicenovic (2000). They concluded that R&D efforts need not be so focused on one technology but instead on a cluster of related technologies, although they should not be spread out too much. As the research and situations are better understood, the portfolio of technologies can be pruned. Recently, a learning-curve tool, EXTOOL (Neij et al. 2003), has been developed in Europe to consider different aspects of wind power generation.

3.06.8 Conclusion

The future of solar power depends on the results of research to find relatively inexpensive ways to convert, transmit, and store solar power. This is not easy. Climate directly impacts the availability of land, and solar power is rather diffuse. Collecting and using this distributed power would require a smart grid to coordinate the collection and a backup base-load system if storage capabilities are not adequately found and deployed. Regional effects such as increased cloudiness and violent storms would impact the collection and maintenance of solar systems.

PV systems do not require much water for operation, but they currently depend on special elements that might become expensive or geopolitically controlled. Research is being conducted to find alternate methods that do not depend on these materials.

While electricity would be a major product of the solar concentrator and solar PV systems, a major use of current fossil fuel in transportation is one not currently easily replaced with electricity. This leaves several options that are being pursued: developing an efficient storage system, charging on the go, or converting solar energy into high-energy-density fuel.

Climate variability impacts solar power through impacts on substitutes as the real price of their operation is better established. While much information needs to be obtained and understanding better developed, one way to look at the problem is as insurance. A case that would cause some difficulty is one where research and development were not ready and effects were causing increased demand for capital to maintain systems such as water management.

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3.07 Energy Production, Conversion, Transmission, and Distribution, Policy, Planning, and Mitigation Process – General Considerations: Infrastructure Vulnerability and Climate

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Glossary

Millennium Development Goals (MDG) is a roadmap of goals based on the United Nations Millennium Declaration:
End poverty
Universal education
Gender equity
Child health
Maternal health
Combat HIV
Sustainability
Global partnership

3.07.1 Introduction

Climate will increasingly affect all aspects of modern societies, global and national economies, energy, underlying infrastructures, as well as all political institutions. The collective effects will cause extensive societal vulnerabilities, whether developed or developing. As such, the increased risks require realistic adaptation responses. In planning responses to the risks, civil and political authorities will have to primarily consider impacts on infrastructures of societies.

The year 2011 was a significant year in the statistics of natural disasters for the past decades, 1981–2011. The total cost of the natural disasters in 2011 was the highest during the aforementioned period and for the first time in the history of the last 30 years the trade deficit of the export-oriented Japan was negative in 2011.

The energy infrastructure is a part of the global infrastructure. Infrastructure consists of durable resources that are classified as 'collective goods' generating external effects. The development of income and standard of living in a society is highly dependent upon its energy resources. During the last decade the productivity growth has been stagnating in the Western industrial countries, thereby reducing the base for private and public consumption. A common characteristic of the industrialized countries is that a diminishing percentage of GNP has been allocated to public investments, leading to reduced growth of the infrastructure stock. This has been happening independently of any climate effects. In this context, we should make a distinction between material and nonmaterial infrastructure. Nonmaterial infrastructure includes the existing technological and organizational knowledge and social networks. On the other hand, the material infrastructure is defined as all physical networks for transportation and communications; that is energy and water supplies, roads, railways, airports, harbors, and construction for post and telecommunications.

Many efforts have been made to define infrastructure. The most restricted description is that infrastructure can be identified from the following attributes (Sarafoglou et al. 2006):

1. Infrastructure is durable capital with a fixed location, and its services have spatial extension, although the benefits decline as distance increases.
2. Infrastructure services satisfy at least one of the following features: (1) polyvalence, (2) temporal generality, and (3) systematic or network functions.

However, the most common definition is that infrastructure is a resource that can be used collectively by many firms and households. Thus infrastructure may be seen as a potential between people and markets.

The importance of different elements of the infrastructure varies among countries and regions depending on, for example, geographical conditions, levels of economic development, and

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sectorial mix of industries. It is important to point out that although the link between economic growth and infrastructure investment is generally strongly accepted by different authors, there are divergent opinions about the quantitative evaluation of the link. The linkages between the energy infrastructure, the transport infrastructure, building infrastructure, and the other forms of infrastructure are also important. For example, a price increase in oil will increase the cost of the transportation infrastructure as well as the cost of capital (e.g., buildings). The interrelationships among the various infrastructures are critical for national economies, and the use of the systems approach is necessary to quantify and assess these interrelationships.

The UN Secretary-General Ban Ki-moon (UN 2011) declared that "Energy is the imperative of the twenty first century." The purpose of this chapter is to analyze the role of energy infrastructure for various economies, the vulnerability associated with energy production and consumption processes, and finally the use of the new paradigm of sustainability in a world increasingly affected by climate.

A sustainable energy infrastructure might be considered one of the most critical policy variables to deal with environment and climate in the future.

Section 3.07.2 presents some facts about energy infrastructure and-methodological assessments. Section 3.07.3 discusses the various aspects of climate vulnerability and energy. Section 3.07.4 presents definitions of hazards and disasters. Disaster databases are reported in Section 3.07.5, whereas precautionary disaster policy is given in Section 3.07.6. In Section 3.07.7, a survey of the concepts of sustainability, sustainable development, and sustainability science is written. In Section 3.07.7, the IPCC and the Stern review are critically reported. Finally, energy futures are discussed in the last section.

3.07.2 Some Facts about Energy Infrastructure and Methodological Assessments

In mythology, energy was connected with the gods. The term energy (*energeia*) was used by Aristotle in his book *Nicomachean Ethics* (fourth century BC).

Kaku (2011) wrote about solar energy in Greek mythology:

> The stars were the energy source of the gods. When Apollo rode across the sky in a chariot drawn by fire-breathing horses, he illuminated the heavens and the earth with the infinite power of the sun.

Energy is one of the most fundamental concepts in physics, but generally, energy means potential for work or change, a rather imprecise definition. On the contrary, energy infrastructure has a definition. The economist Nicholas Georgescu-Roegan advocated in his ground-breaking book (1971) that the economic system was actually a general thermodynamic systems.

The energy infrastructure includes the electricity grid of transmission lines, the physical network of pipes for oil and gas, the rail network, marine transportation, and truck lines. The electricity infrastructure consists of power plants fueled by coal, oil, or gas. We are discussing here the electric grid and not portable (battery), or alternative energy sources (e.g., wind, photovoltaic, and ocean wave energy production). Human climate forcings, such as carbon dioxide and aerosols from fossil fuels, land use management, and so on (NRC 2005), may generate climate instability and lead to extreme weather events. These instabilities and extreme events can cause critical water and food shortages for many people on earth.

There are some path-breaking works in the history of energy-related issues. W.S. Jevons' book *The Coal Question* (1865) was an early economic analysis of the depletion of coal resources. The mathematical economist Hotelling (1931) developed an intertemporal price mechanism for nonrenewable resources. The bell-shaped curve of world oil production was developed by the geologist Hubbert (1956). This is the so-called Hubbert's peak. His prediction of the 1970 peak of US oil production was verified.

Two main complementary approaches have been used to analyze the role of energy infrastructure:

1. A parametric approach using the Cobb–Douglas production function.
2. A nonparametric approach using Data Envelopment Analysis (DEA).

A common characteristic in infrastructure literature is the production function formulation relating value-added output Q to the quantities of input L, private input C_p, and public infrastructure C_i.

If the parameters of this formulation of production function are estimated, the resulting method is termed the parametric approach. The following production function is a typical parametric application in which the parameters are estimated by the use of econometric techniques.

$$Qk = F(L, C_p, C_i)$$

Various specifications of the production function have been used. The Cobb–Douglas function is still the most frequent specification. More complicated functions have also been applied, such as the trans log function and the Mills and Carlino formulation (1989).

However, a number of infrastructure studies may be found in which public infrastructure capital C_i has not been incorporated into their production or cost functions. An obvious implication of this misspecification in which the C_i is an omitted variable is that all the empirical results may suffer from an omitted variable bias.

In the nonparametric approach (DEA), the parameters of the production function are not estimated, but relative efficiency indices are calculated reflecting input–output differentiation among various units. The name DEA derives from the procedures applied to observational data used to establish efficiency frontiers via an envelope function of all production process. A mathematical programming model applied to input–output data gives estimates of extremal input–output relations similar to the production function. Forsund and Sarafoglou (2002) offer a historical review of DEA in economics and operations research. An excellent survey of energy and environmental modeling using DEA and other nonparametric methods can be found in Zhou et al. (2008). Emissions are classified as undesirable outputs in the DEA approach.

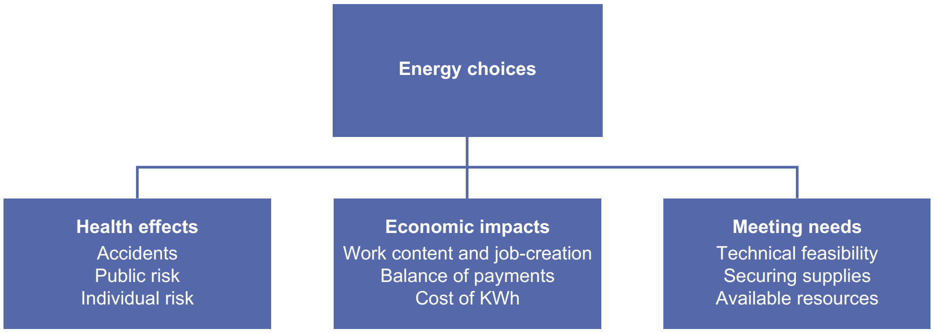

Figure 1 Energy choices. Source: Siskos, J., and P. Hubert, 1983: Multi-criteria analysis of the impacts of the energy alternatives. *Eur. J. Oper. Res.*, **13**, 278–299.

The compatibility of the parametric and nonparametric approaches might be rather unsatisfactory, but future development seems promising.

Another approach to estimate the economic effects of infrastructure investments is cost benefit analysis (CBA). In CBA, the economic effects of the infrastructural investment are measured as increases of the consumer surplus of the estimated demand function.

Energy choices are very important because they generate health effects, economic impacts, and the efficacy considerations for workers, users, and the public. Siskos and Hubert (1983) wrote an interesting application of multicriteria analysis (MCA) of the impacts of energy alternatives in France.

The energy infrastructure has a direct impact on the labor market: job creation, work content, and job elimination are related to the energy choices.

The balance of payment can be changed by the value of energy imports. The cost of KWh is an extremely important factor for energy decision making of individuals, government agencies, and firms (Figure 1).

How can governments meet the energy needs of their citizens and corporations in the era of globalization?

What is the optimal distribution of domestic energy production and energy import given the political instability of the world? The risks related to the production, distribution, and use of energy are critical for economic systems as well

3.07.3 Climate, Vulnerability, and Energy

It was mentioned earlier that climate will increasingly affect all aspects of societies, economies, energy, underlying infrastructures, and political institutions, as well as the world's ecosystems. The collective effects will create extensive vulnerability in societies, whether developed or developing.

Rockstrom et al. (2010) tried to link the three disconnected processes (climate, ecosystem, and Millennium Development Goals (MDGs)) in Figure 2. Climate, including possible changes in regional and local climatology, is a major threat to the ecosystem and to human society. Environmental degradation and biodiversity loss are also big challenges for the climate and the human population. Anthropogenic emissions can influence the ecosystem and the climate.

Svante Arrhenius, a scientist from Uppsala (Sweden) and a Nobel laureate, developed the theory in '*Varldarnas utveckling*' (1906) that changes in carbon dioxide quantity in the atmosphere could change the earth's temperature through the hothouse or greenhouse effect.

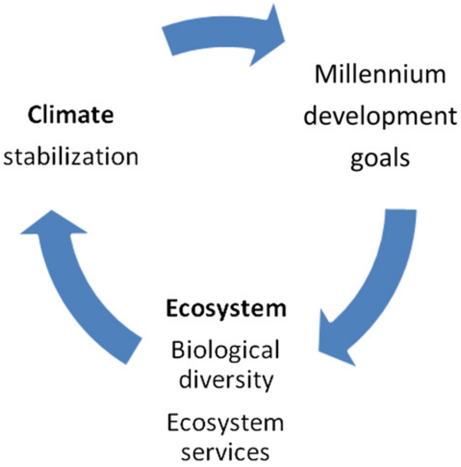

Figure 2 Disconnected critical processes. Source: Rockstrom, J., et al., 2010: Making progress within and beyond borders. *Global Sustainability*, H. J. Schellnhuber et al., Eds., Cambridge Univ. Press.

> By the influence of the increasing percentage of the carbonic acid (CO_2) in the atmosphere, we may hope to enjoy ages with more equable and better climates, especially as regards the colder regions of the earth, ages when the earth will bring much more abundant crops than the present, for the benefit of rapidly propagating mankind.

and Arrhenius' greenhouse law can be formulated:

> if the quantity of carbonic acid increases in geometric progression, the augmentation of the temperature will increase nearby in arithmetic progression.

Arrhenius' temperature increase forecast for the doubling of CO_2 in the atmosphere was very accurate in the precomputer era. It is interesting to note that, the hothouse or greenhouse effect was forgotten by scientists until the 1960s.

Vulnerability might be considered as a function of vulnerability of assets and resilience of non-assets. The IPPC's definition is that vulnerability is the propensity of groups, systems, or persons to suffer harm, or anticipate and cope with, resist, and recover from stressors. The World Bank and UN definition (2010) is rather similar to IPCC's: Vulnerability is a characteristic that influences damages in physical assets (building architecture, codes, and strength), social capital (family networks, trust, social structure), and political access (government help and participation in policies).

Another definition of vulnerability was given by the Friibergh *Workshop on Sustainability Science* (2000) in Sweden, vulnerability can be defined thus:

> Vulnerability analyses seek to evaluate the risk of adverse outcomes in the face of climate variability and longer-term change and the other relevant causal factors that co-exist with climate.

Vulnerability (V) can be seen as the difference between Cumulative Impacts (I) from multiple stressors and Adaptive Capacity (AC):

$$V = I - \mathrm{AC}$$

There are many perspectives on vulnerability. In Pielke's web page (2011) there are two other perspectives:

A. Outcome vulnerability
B. Contextual vulnerability

The first vulnerability is an IPCC-based climatic vulnerability. The second vulnerability is bottom-up and has higher complexity in terms of institutional, economic (water, food, health, and energy), and social structures, climatic factors, and finally ecosystems.

The global energy generation process is quite complex and has a high spatial concentration. Changes in environmental and climate statistics can generate undesirable energy infrastructure shortages (Paskal 2010).

We know that the energy infrastructure has a long lifespan (50–100 years), high building costs, and high maintenance costs. The Hoover Dam in the United States is 75+ years old, the first English nuclear in Calder Hall was in use during the period 1956–2003, and so on. It is difficult to maintain the old energy infrastructure so as to satisfy modern environmental impact assessments. If there are changes in precipitation patterns, then precipitation-dependent hydroelectric power stations could face new difficulties. Deforestation could generate landslides and affect the flow of hydroelectric power plant water.

During the hot 2003 summer (temperature $>40\,^{\circ}\mathrm{C}$) in Europe, many nuclear plants had to be unused, and European countries imported energy at higher prices. Higher energy prices can increase national economies' budget deficits.

Other weather-related events can harm national and regional economies. Hurricane Katrina in 2005 damaged almost 20% of the United States' refining capacity. The city of New Orleans lost almost 25% of its population during the post-tornado period.

Cold weather has stopped the oil flow of the Alaska pipeline many times during the last 10 years. The world consumption of oil today is almost $160\,000\ \mathrm{l\,s^{-1}}$. The spatial distribution of oil production is concentrated in politically unstable regions (e.g., OPEC nations).

The distributional aspects of energy consumption are also important to mention here for energy vulnerability: Nine million Swedes consume more energy than Indonesia's 200 million citizens.

In other words, the uneven spatial distribution of energy supply (e.g., OPEC nations) and energy demand (e.g., developed countries) increases global vulnerability.

3.07.4 Hazards and Disasters

Natural disasters have a long historical record. Plato in his dialogue *Timaeus and Critias* (360 BC) described that Atlantis (the island of Atlas) sank into the ocean in ~9000 BC "in a single day and night of misfortune." This information was confirmed by reading the Egyptian hieroglyphs and was disseminated by the lawmaker Solon.

Although the terms hazard and disaster have an overlapping meaning in everyday life, they are assumed to have different meanings here.

Hazard is a probability of a natural event that might cause harm and should be estimated by experts, whereas disaster is the output of a hazard and might be estimated by a multidisciplinary team of experts.

The risk exposure is a function of the population and assets in a given area.

Countermeasures to reduce vulnerability can be classified according to World Bank:

- Mitigation (to minimize GHG emissions so as to minimize extreme weather events)
- Prevention (to build a plinth-wall for floods)
- Preparedness (to plan building evacuations)
- Relief (to help people after a disaster)

Finally, disaster risk is a multiplication of hazard, exposure, and vulnerability.

Total disaster impact is the sum of direct and indirect effects. Direct disaster impacts can be estimated in terms of human and capital loss. Indirect disaster impact in an economy is more complicated to estimate because it deals with the changed structure of the economy (e.g., production, consumption, employment) after the disaster.

Other socioeconomic factors are extremely important to gauge total disaster impact. The level of development of a nation is critical for the absorption of disasters. For example, Haiti's last earthquake was less on the Richter scale than Chile's last earthquake, but damage absorption was much better in Chile than in Haiti.

The development of the theory of economics on natural disasters since the seminal work of Dacy and Kunhreuther (1969) has been modified and directed to the economics of climate (Nordhaus 2006; Stern 2007).

The insight of this research-evolution is that global warming might be the cause of most natural disasters. The empirical work for the effect of natural disasters on national economies in terms of capital and human losses has been increased in the last 20 years (Alexander 1997; Cavalo and Noy 2009).

Although there is no widely accepted definition of natural disaster, the CRED definition from Belgium is used here:

> Situation or event which overwhelms local capacity, necessitating a request to national or international level for external assistance; an unforeseen and often sudden event that causes great damage, destruction and human suffering.

Preventing disasters means using policies that minimize exposure and vulnerability to human suffering and destruction. Exposure relates to the people and property subject to hazard. It is a function of population density and location indicators.

These three factors determine how some communities can absorb disasters and recover more easily than others.

Natural disasters can be classified into three categories:

1. Hydro-meteorological: floods, droughts, landslides
2. Geophysical: earthquakes, volcanic eruptions
3. Biological: epidemics

The severity and frequency of disasters in the last several decades have generated an increased interest in data and methodologies to better understand disaster complexity. Disaster impact on the development and growth of nations became an important issue for investigation.

The prediction of disasters has been one of the main themes for many research works in social and natural sciences. Ongoing improvement in data quality may lead to increased disaster prediction accuracy.

Disaster issues have been investigated by both natural and social scientists (mainly economists, sociologists, and political scientists) in an interdisciplinary way. A more holistic disaster approach has been conducted by scientists lately, which is very promising.

Finally, a 'before the disaster' policy can be exemplified by the reallocation of the Tokyo metropolitan area. A review of this is given in Section 3.07.6.

Public policy makers need more quantitative data so as to assess disaster risks and generate preparedness and mitigation planning.

3.07.5 Disaster Databases and Methods for Estimation of Disasters

Questions such as "to what extent can existing data and methodologies be reliable for disaster assessment" are important for public policy makers.

The lack of systematization and standardization is the main problem of disaster statistics. Data collected by insurance companies for risk management can be biased. Low-income countries or groups are not included, because they can afford insurance policies and costs.

1. Emergency Events Database (EM-DAT) generated by the Center for Research on the Epidemiology of Disasters (CRED) at the University Catholique de Louvain, Belgium (www.cred.be). This database (**Figures 3 and 4**) has been generated from various agencies (e.g., UN, insurance companies). EM-DAT covers only direct damages (i.e., damage in housing, infrastructure, farming and number of people killed during the-disaster).
2. Sigma, Swiss Reinsurance Company.
3. NatCat, Munich Reinsurance Company.
4. Disaster Database Project, University of Richmond.
5. Hotspots Project Database, Center for Hazards Risk Research, Columbia University.
6. Google Insights Google has developed a database based on web search statistics. The web search database might be very recent (e.g., 2- to 3-days-old data) and is a proxy of an event.

The most frequent methods for estimation of disasters are the UN-ECLAC and the econometric methods (Albala-Bertand 1993; Noy 2009; Okuyama and Sahin 2009).

A simple econometric model used by Cavalo and Noy (2009) is:

$$\mathrm{DIS}_{\mathrm{it}} = a + bX_{\mathrm{it}} + e_{\mathrm{it}}$$

where the variable DIS measures the material and human losses of country i at time t, the variable X_{it} measures the disaster magnitude and vulnerability of the country, and e_{it} is the error term.

The level of economic development of a country in terms of per capita GDP may increase its vulnerability to the impact of natural disasters.

The rationale of this hypothesis is that developed countries have more mitigation policies to minimize the effects of disasters (e.g., political stability, property rights, earthquake engineering, and better urban and rural planning).

Dacy and Kunreuther used a simple neoclassical version of Solow–Swan growth model of capital stock (K) and labor (L):

$$Y = f(K_{\mathrm{p}}, K_{\mathrm{b}}, K_{\mathrm{r}}, L)$$

where the capital stock has been disaggregated in public capital (K_{p}), business capital (K_{b}), and residential capital (K_{r}).

The optimal path of recovery can be examined by imposing marginal productivity conditions. In this type of model, technological replacement is more critical than technological progress. More sophisticated growth models with endogenous technological progress can be used in a natural disaster context.

Spatial econometric models of natural disaster impacts have been used as well. Space, friction, spatiotemporal components, externalities, and many other aspects interact and should be treated adequately in spatial econometrics (Sarafoglou and Paelinck 2008; Saldana-Zorrilla and Sandberg 2009).

Alternative methods for the estimation of disasters are as follows:

1. International Institute for Applied Systems Analysis (IIASA) Models
2. Input–Output Models
3. Social Accounting Matrix Models
4. Computable General Equilibrium Models
5. Geographical Information Systems and Remote Sensing

3.07.6 Precautionary Disaster Policy and the Great East Japan Earthquake

The role of environmental factors and risks in the decision making of 'relocation of capital functions' out of Tokyo is given in this section. The short- and long-term costs of the great

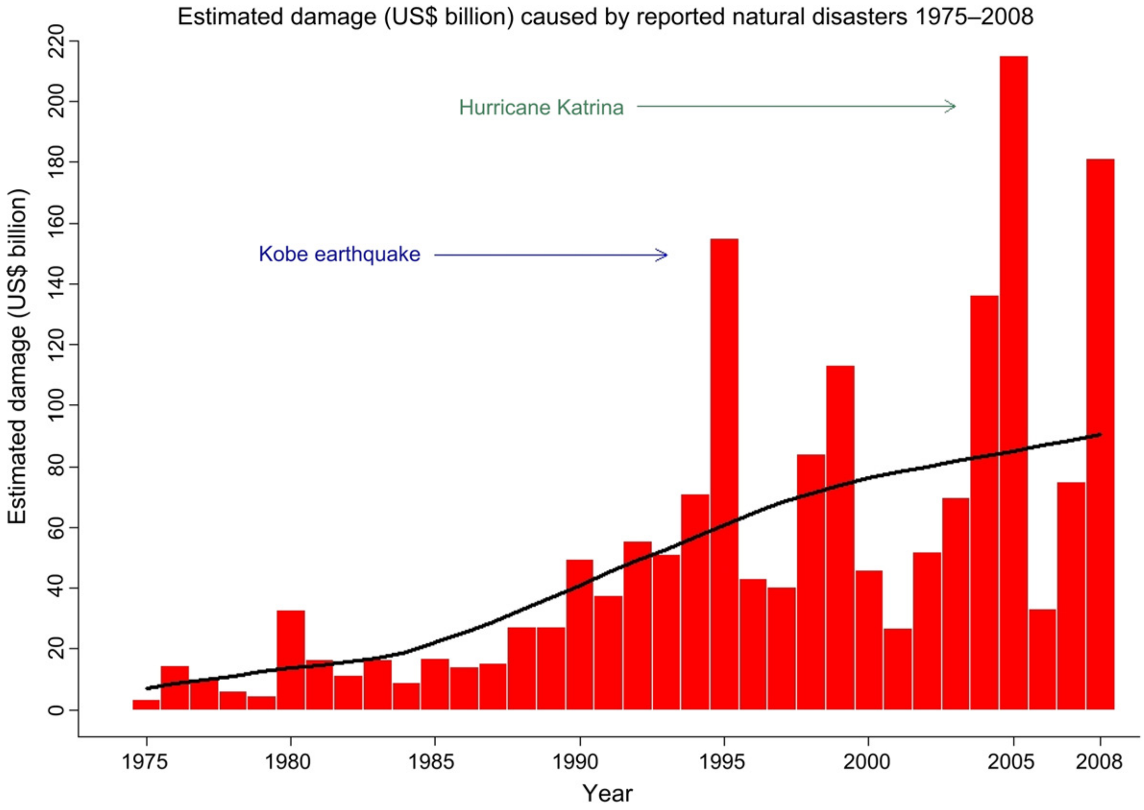

Figure 3 Natural disasters. Source: EM-DAT.

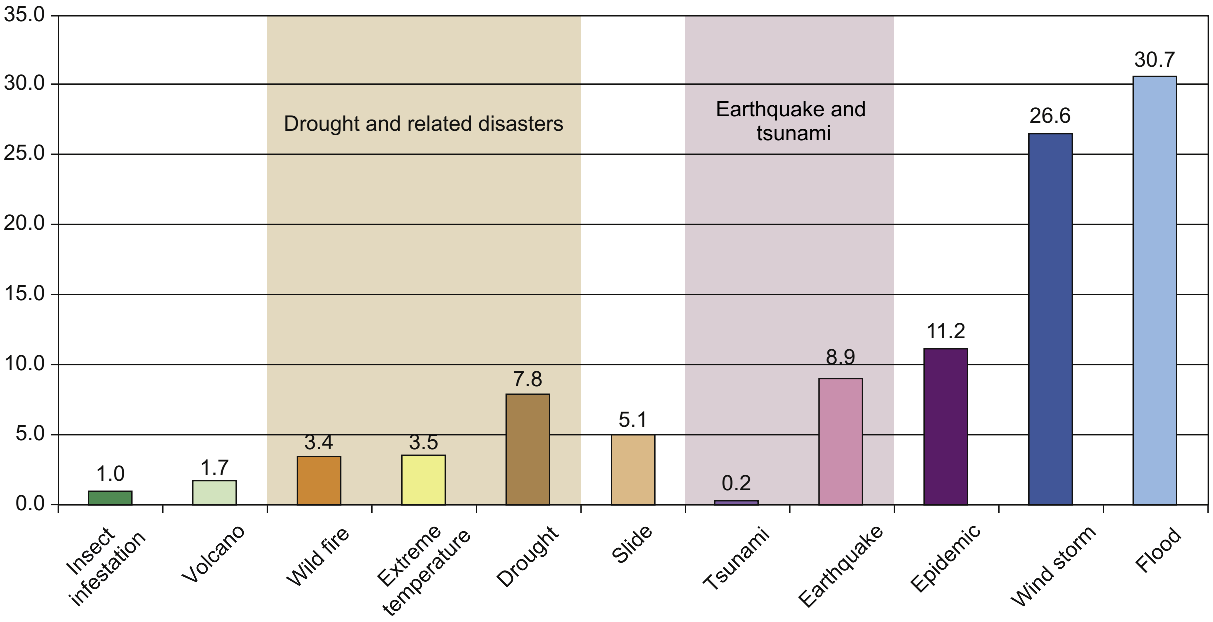

Figure 4 Distribution in percentage of natural disasters by type, 1991–2005. Source: EM-DAT.

Japanese Tohoku–Sendai earthquake, March 2011, are reviewed after the relocation introduction.

Tokyo is one of the megacities of the world, with more than 18 million people. The major problems of Tokyo are the high population density, pollution, and transportation congestion. In addition to these problems, future natural disasters (e.g., earthquakes, volcanoes) have been identified as major problems for the existence of Tokyo.

The Government of Japan (the National Diet) decided in 1992 to 'split' the Tokyo metropolitan area: first, to generate a new satellite city ('Washington, DC') for the Diet, the Prime Minister's Office, the Supreme Court, and other government agencies out of Tokyo (relocation of capital functions); and then for the rest of Tokyo to have a 'New York'-type function as Japan's economic center. The budget of this project was ~$12 billion.

A Council of 'wise men' was generated to find the optimal place for the Japanese 'Washington, DC.' The Council formulated 16 criteria for the new place.

Most of these criteria involved logistics and networking the Tokyo metropolitan area with the rest of the country and foreign countries.

Two environmental criteria were imposed:

1. Harmony with the natural environment
2. The possibility of lessening the environmental load

Furthermore, the following natural disasters criteria have been used:

1. Safety in the event of an earthquake disaster
2. Safety in the event of a volcanic eruption
3. Safety against flood and sediment disasters
4. Speedy response in a large-scale disaster

These disaster criteria might be seen as risk dispersion and resilience increase to disasters. If Tokyo would have a large-scale disaster in the future, the possibility of simultaneous large-scale disasters in the satellite city must be minimal. However, this brilliant project was not approved by the next Japanese government because of land speculation and other political considerations, and the project was neglected.

The Fukushima Daiichi (Fukushima 1) nuclear accident in 2011 revitalized the project once again, but the government must find a new place for the satellite city of Tokyo. The main nuclear accidents before Fukushima 1 were Chernobyl (USSR) in 1986 and Three Mile Island (USA) in 1979.

Fukushima was a multiple disaster:

- Great East Japan Earthquake (magnitude 9.0 R)
- 600 aftershocks (magnitude 5.0 R or greater)
- Tsunami (15 m waves)
- Nuclear explosion

The plant was commissioned in 1971 and had 40 years of operation before the accident. The electrical output was 4.7 gigawatts, and the type of reactor was 'boiling water with containment vessel.' The cause of the accident was that the tsunami destroyed the cooling system of the plant.

What are the effects of this nuclear explosion for the Japanese economy? First, 20 000 inhabitants died or are missing, and >6000 inhabitants were injured. The exclusion zone area in Fukushima is 20 km 1 year after the explosion. The government relocated 350 000 people during the first year. The radiation released in the area was ~400 PBq. Decommissioning will take between 30 and 40 years.

The effects of the nuclear radiation during the decommissioning period on agriculture, water, food, climate, health, and industrial production are impossible to estimate now, although there is some statistical information for the year 2011.

The year 2011 was a significant year in the statistics of natural disasters during the period 1981–2011. The total cost of the natural disaster (buildings, lifeline utilities, social infrastructure, and others) in 2011 was the highest during the aforementioned period, almost ¥17 trillion. The trade deficit of export-oriented Japan was negative in 2011 for the first time in the history of the last 30 years, but the macroeconomic impact in terms of real GDP changes is expected to be much less than after the 'Lehman shock.'

The Japanese government developed reconstruction plans for its sustainable rebirth. The following list describes the actions taken:

- A new 'Reconstruction Agency'
- ¥23 trillion budget in the next 10 years
- Tax incentive system and fiscal health
- Disaster risk reduction
- Disaster relief
- Subsidy to locate industries in Japan
- Reconstruction open to the world (kizuna)
- Additional public infrastructure projects
- Land use restructuring
- Building regions that respond to the challenges of an aging society and disaster reduction
- Promoting the introduction of renewable energy
- Developing disaster resilient information network
- Creating 'eco-towns'
- Supporting small- and medium-sized enterprises
- Testing radiation of export products and rigorous radiation monitoring
- Designing decontamination roadmap for special areas
- Designing roadmap toward decommissioning of Fukushima Daiichi, TEPCO
- Speedy supply chain recovery

Source: National Policy Unit, March 2012.

The future of nuclear plants is presently uncertain in Japan. There are three major issues: (1) How many nuclear plants will Japan have in the future? (2) Will nuclear plants be nationalized? The Fukushima Daiichi was a private power plant managed by the company TEPCO. (3) What will be the optimal ratio of imported electricity to the electricity produced in Japan? There are other dynamics for post-Fukushima Japan as well. The big car companies such as Honda want to move away from Japan to other countries. They consider that Japanese natural disasters can be adverse to their economic future.

3.07.7 A Survey of Sustainability, Sustainable Development, and Sustainability Science

Following the survey of Grober (2007), the authors found out that the SD-definition (nachhaltigkeit) had been minted by German Royal Mining Officer Hanns Carl von Carlowitz in 1713. Von Carlowitz wrote a comprehensive book (~400 pages) of forestry management called *Sylvicultura oeconomica* (1713). *Anweisung zur wilden Baumzucht* dealt with the conservation and cultivation of timber. At that period, timber was a strategic resource like oil is 260 years later.

Sustained yield (*nachhaltigkeit*) was diffused in other parts of the world through the work of Alexander von Humboldt and the 'father of ecology,' Ernst Haeckel. The French translation was production soutenu, soutenabilite, or durabilite, but the word *soutenir* is based on the Latin verb *sustenere* (uphold). The etymology in Spanish is either *sostenibilidad* (from *sostener*) or *sustenabilidad* (from *sustentar*). The first term has the passive explanation (being upheld), and the second a more active explanation (to uphold). Also, the English translation sustainability has the same Latin origin, *sustenere*.

Similarly, the term sustainability in Norwegian is *baerkraft*, in Greek *viosimotita*, and in Swedish *hållbarhet*.

The term *nachhaltigkeit* has been used mainly in German forest management references since its original publication. The English translation became popular in the last decades of the twentieth century by international organizations (e.g., Club of Rome), the European Social Democrats (Olaf Palme, Willy Brandt, and Gro Harlem-Brundtland), and finally by the United Nations' and World Bank's massive research programs.

An earlier environmental work was *The Limits to Growth* (1972). The *Limits* was written by a group of scientists from MIT under the leadership of Dennis Meadows and Donella Meadows. The main purpose was the investigation of the long-term causes and consequences of the finite nature of resources. The main model variables were growth in population, industrial capital, food production, resource consumption, and pollution.

A methodology used on computer programs called Dynamo was based on the theory of System Dynamics of Jay Forrester (1971). The project was financed by the Club of Rome. Their main pessimistic conclusion was that "the limits to growth on this planet will be reached sometime in the next hundred years." But the MIT team also had an optimistic conclusion that under the assumptions of zero population and capital growth it could be possible "to establish a condition of ecological and economic stability that is sustainable far into the future."

The following newspaper headlines appeared in 1972:

"A computer looks ahead and shudders"
"Study sees disaster by year 2100"
"Scientists warn of global catastrophe"

The book *Limits to Growth* is considered the first environmental book in history that had a massive impact and public support (9 million books sold and translated into 30 languages).

Some economists have pointed out that *The Limits* was the theoretical framework of the energy crisis. The reason was that the OPEC countries understood they have great bargaining power in oil price negotiations with other countries.

The Limits was not only important to the discussion about our future, but also mobilized the United Nations and the World Bank to become more active in world environmental issues.

The first UN Conference on the Human Environment took place in Stockholm in 1972. The subject of the conference was the 'nonlocality' or internationalization of lake pollution. Scientists found contamination from pollutants in Swedish lakes from Poland and other Baltic countries. Olof Palme was the representative from Sweden, and he invited Indira Gandhi as one of the main representatives of the developing world. The communication that resulted was not particularly effective between the representatives of the developed and the developing world.

Gandhi stated that "poverty is the worst pollution," and the representatives understood that a big gap existed in the concept of pollution and economic priorities between the developed and developing world.

Furthermore, if we read the conference documents, we find some normative recommendations for the wise use of natural resources. One of the most important recommendations of the conference was the monitoring of pollution.

The then president of World Bank, Robert McNamara, announced the idea of establishing a commission of politicians and technocrats. In 1977, the former German Chancellor and Nobel laureate for 'Östpolitik,' Willy Brandt, became the chairman of this commission – the Independent Commission on International Development Issues (the Brandt Commission). This helped to improve the climate of North–South (developed world-developing world) relations. Olof Palme was a member of the Commission too following his Stockholm Conference experience.

The Brandt Commission published two books: *North-South* (1980) and *Common Crisis* (1983). These books dealt with issues like environment, food, energy, trade, population growth, development, and negotiations.

It is worth mentioning some works related to the environment between the publications of *The Limits* and the Brandt Commission.

The 'World Council of Churches' (WCC) in a world conference in Bucharest (1974) used the term "just and sustainable society."

The World Wildlife Fund (WWF) in cooperation with UNEP and the International Union for the Conservation of Nature (IUCN) published a declaration in 1980 called a "Living Resource Conservation for Sustainable Development."

The UN General Assembly generated the World Commission on the Environment and Development (1983) under the leadership of the Norwegian politician Gro Harlem-Brundtland (GHB). Their work, *Our Common Future* (1987), was published years later. GHB used the previous work of Brandt, WWF, WCC, and Meadows and she was the mother of a new concept: sustainable development (SD).

They defined 'sustainable development' as "development which meets the needs of the present without compromising the ability of future generations to meet their own needs." They continued by pointing out that energy consumption should be more ecology oriented:

Sustainable global development requires that those who are more affluent adopt life-styles within the planet's ecological means – in their use of energy, for example.

In other words, SD is a new development concept and new long-run economic policy. It is an intragenerational and intergenerational comparison of utility or consumption.

The commission made the idea of SD politically acceptable for both developed and developing nations. This was a historical moment for setting the beginning of the unification and communication between different countries of the world.

However, there is a 'scarcity of plenty' definition of sustainability. Solow (1988) has defined sustainability as maintenance of production opportunities or 'certain standards of consumption/living possibilities over time.'

Ecological economics might be a system of knowledge that combines the management of households (economics) with the housekeeping of nature (ecology).

The ecological definition of Eriksson and Andersson (2010) might be:

> An ecological system being sustainable if it is resilient.

Resilience must satisfy these conditions:

- The degree to which the system is capable of self-organization.
- The ability to build and increase the capacity for learning and adaptation.
- The amount of change the system can undergo and still retain the same controls on structure.

The physics Nobel laureate Gell-Mann (2010) gave a new definition:

> … sustainability refers to quality of human life and of the environment that is not gained at the expense of the future.

He continued with the economic transition for sustainability.

> The economic transition must, of course, involve what economists call 'the internalization of externalities'. Prices will have to come much closer to reflecting true costs, including damage to the future.

This complicated price estimation has important energy substitution effects. However, we note that renewable energy technologies might be financially competitive with nonrenewable energy technologies in the future because of research and development as well as technological development.

A more operational definition of sustainable development has been given by IUCN et al. (1991), as "improving the quality of human life while living within the carrying capacity of supporting ecosystems."

In the last 10 years, a new sustainability science has emerged based on the interrelationships between society, the earth, and the post-GHB literature. Some core questions were asked in an interdisciplinary policy forum for the nature of Sustainability Science (2001):

1. What systems of incentive structures – including markets, rules, norms, and scientific information – can most effectively improve social capacity to guide interactions between nature and society toward more sustainable trajectories?
2. How can today's relatively independent activities of research planning, monitoring, assessment, and decision support be better integrated into systems for adaptive management and societal learning?
3. What determines the vulnerability or resilience of the nature–society system, in particular the kinds of places and particular types of ecosystems and human livelihoods?

Sustainability has been a success story for the last 20 years. The number of documents of sustainable development can be estimated at ~21 500 000 as of 2011 (Bettencourt and Kaur 2011).

This statistical evidence of sustainability documents demonstrates that sustainability science has an increased scientific impact and longevity.

3.07.8 The IPCC, the Stern Review, and a Critique of Top-Down Modeling

The IPCC was organized by the joint effort of the United Nations and the World Meteorological Organization (WMO). The main idea behind the IPCC was economies of scale in research by using large international groups of scientists and the increased credibility of the research outcome by the scientific community. The science and knowledge evolution has been based on individuals or small groups (5–12 scientists) throughout history.

The IPCC configuration was a scientific trend of discontinuity. The IPCC groups were composed of more than 1000 scientists in each group, with a flexible time and labor input. Although the IPCC monopolized (or oligopolized) the climate debate during the last 20 years, there is an increasing critique among scientists of IPCC's scientific evidence.

The four IPPC studies on sustainable development (1988–2007) have evolved gradually.

The discussion on sustainable development in the IPCCs has the following dynamics:

The first assessment report (AR1) focused on the technology and cost-effectiveness of mitigation strategies. The second assessment report was broader than the first. The issues were related to equity across countries and generations, as well as environmental and social considerations. The focus was even broader in the third assessment report (TAR), with three classes of analyses or perspectives: efficiency and cost-effectiveness, equity and sustainable development, and sustainability and societal learning. Many IPCC expert group meetings supported the TAR with emphasis on social dimensions of climate and sustainable development.

In the fourth assessment report (AR4) the complexity of sustainable development is more prominent and includes:

- Concept
- Environmental, economic, and social dimensions
- Climate mitigation development choices in a modeling context
- Impact of mitigation options on sustainable developments goals
- International sustainable development policies
- Adaptation practices, option constraints, and capacity
- Interrelationships between adaptation and mitigation
- Adaptation and sustainable development

The essence of this assessment is 'climate first.' Climate first is determined by government-driven, climate-specific measures that impose limitations of GHG emissions. The risks of climate are functions of these measures.

Another interesting issue is the relationship between economic development and climate.

"Making development more sustainable" is a critical balance of environmental, social, and economic dimensions for developing nations. Finally, interactions of state, market, and society can influence the mitigation of climate.

At the end of his political career, the English Prime Minister Tony Blair had the ambition to follow in the footsteps of Willy Brandt and GHB in building a commission to analyze the effects of climate in the new millennium. Finance Minister

Gordon Brown generated the necessary financial resources for this commission, but Blair resigned and Brown became prime minister.

The leader of this commission was Nicholas Stern, a chief economist from the World Bank. Because of the political conflict between Blair and Brown, neither man could give his name to the commission. In 2006, Stern published the research of this commission, the so-called Stern Review.

The Review was based on statistics from TAR, but the economic analysis of the Review was far beyond the TAR analysis.

The main Review conclusion was that the world economy should decrease GNP growth by 1% so as to finance the reduction of GHG emissions toward a sustainable world future. This conclusion generated a lot of reaction by economists and geoscientists, but it was used by the AR4. In other words, sustainability has a monetary cost. Is there any willingness to pay for this sustainability?

The political scientist Roger Pielke Jr. gave an answer in his well-cited book, *The Climate Fix* (2010): "When policies on emissions reduction collide with policies focused on economic growth, economic growth will win every time." Pielke's realistic answer generates limitations for climate policies.

Both the IPPC basic models and the Stern Review model are top-down models.

The difference between top-down models and bottom-up models is outlined below.

In top-down 'socialistic' economic models, the central planner can comprehend the mechanism of the system and is able to calculate the set of optimal prices. The market system is not necessary in this type of model.

If we use top-down (the cathedral) environmental models, we may not achieve policy coherence among national, regional, and local levels. For example, the executive (decision maker) makes a decision, and this decision is disseminated to the lower levels in the hierarchy. The economist Oscar Lange used the Soviet economic planning system as a typical example of the top-down approach.

The bottom-up model can achieve better policy coherence among national, regional, and local levels on environmental and energy issues. Nobel laureate Hayek (1945) described the bottom-up model with the use of the market system (bazaar). Individuals cannot understand the information complexity of the market, although they can understand partial information bits.

The role of the markets is the aggregation process of information. In managerial decision making, the bottom-up organization is the one that functions from the grassroots. The information direction is from the inferior to superior.

The top-down versus bottom-up debate migrated from economics to other fields, for example, regional science, environmental studies, architecture, software engineering, public health, and atmospheric science.

In computer science, a successful application of bottom-up thinking is the program Linux. The father of Linux was the Finish computer scientist Linus Torvald, who decided to have open-source software with a free 'source code.' This noncommercial, nonproprietary, and collaborative approach is more successful than the top-down and the protected Unix software.

The Nobel Prize in Economic Science in Memory of Alfred Nobel (2009) of Elinor Ostrom was very radical. The Royal Swedish Academy of Sciences cited Ostrom's work "by showing how common resources – forests, fisheries, oil fields or grazing lands, can be managed successfully by the people who use them, rather by governments or private companies."

Her Nobel prize lecture was called, "Beyond Markets and States: Polycentric Governance of Complex Economic Systems."

Two comments for this prize can be written here:

1. Ostrom was the first environmental social scientist to win the Nobel Prize in Economic Science since its inception.
2. Her polycentric governance of commons was based on self-organization and the bottom-up approach.

New paradigms in mathematics, such as complexity theory and fractal geometry, changed the notion of traditional dynamics (Sarafoglou 1994). The path-breaking works of Thom, Lorenz, Mandelbrot, and Prigogine left footprints in the "idea of control from the bottom-up came onto the agenda." The urban geographer Michael Batty (2005) wrote that "the notion of smooth change was quickly abandoned as ideas concerning catastrophe theory, bifurcation, chaos came onto agenda. The notions of systems being far-from-equilibrium took hold. The notion of positive feedback is essential to these dynamics."

The Santa Fe Institute was an important intellectual hub for the implementation of path dependence and bottom-up system evolution, but the superstructure of this evolution is now much bigger.

3.07.9 Future Studies in Energy

The famous Danish physicist Niels Bohr said, "Prediction is very difficult, especially about the future." In the past, very few authors could predict the future with high accuracy.

Jules Verne in the late 1800s (urban life, astronaut mission, and deep sea), Leonardo da Vinci in the late 1400s (airplane, helicopter, and adding machine), and the 'noir prophet' William Gibson (World Wide Web) in his *Neuromancer* (1984) were the most famous authors.

There are some certainties for the future energy market, such as the gradual transition from nonrenewable to renewable sources and the increased efficiency of energy use.

Table 1 Energy futures during the period 2012–2100

Near future (2012–30)
Solar power, wind power, hydrogen, electric car, nuclear fission, improved internal combustion, alternative fuels, storing sunshine, capturing carbon, solar-thermal engine, microbial fuel cell, better bioreactors, and artificial photosynthesis.
Mid-future (2030–70)
Pollutants into the atmosphere, algae blooms, carbon sequestration, genetic engineering, fusion power, hot fusion, fusion by laser fusion in a magnetic field, tabletop fusion.
Far future (2070–2100)
Magnetism, the magnetic car and train, space solar power

Source: Scientific American, 2012: Scenarios for a Clean Energy Future, March 11; and Kaku, M., 2011: *Physics of the Future*, Doubleday.

We do not know the spatiotemporal information and the most dominant form of energy of the future, but we should speculate for the energy forms of the near, mid, and the far future (Table 1).

Finally, will we have an energy crisis in the future?

Can scientific progress solve the increased energy demand problem?

Can the world leaders increase their efforts to accommodate new forms of energy?

The Greek politician Perikles (fourth century) had a pragmatic view of the future, "It is not important to know the future but rather to be prepared for it."

3.07.10 Conclusions

Deffeyes (2006) wrote, "It will be more orderly if we were to generate a blueprint for a society constrained by the availability of resources. Then we need a noncatastrophic pathway that takes us from here to that blueprint. Welcome to the post-Hubbert world, the world beyond oil."

In the post-1973 energy crisis period, two main energy infrastructure trends for the decarbonization of energy have been observed:

1. A temporal increase of energy efficiency (or the dynamic efficiency) through technological improvements and substitution from nonsustainable (nonrenewable) energy to secure sustainable (renewable) energy is possible through carbon taxes.
2. Dynamic efficiency can reduce the supply energy, and the substitution can reduce energy demand; this energy substitution might be more quantitative and qualitative in the future.

Our conclusions for the sustainability paradigm of energy infrastructure are as follows:

1. The Brandt Commission and GHB Commission's conceptual framework for the North–South equity relations should be continued and be applied for the energy infrastructure and the energy poverty (Kash et al. 1976; Lovelock 2006; Schellnhuber et al. 2010).

   The climate is a local, national, and global issue, and the cooperation of all nations is critical for reduction of GHG emissions and natural disasters. Sustainable development is one of the most important goals of the twenty-first century and one of the Millennium Development Goals (MDGs). The year 2012 has been declared by the United Nations General Assembly as the "International Year of Sustainable Energy for All." The main commitment of the Secretary-General's vision is "Sustainable Energy for All will revitalize the global economy, improve social; equity and protect the ecosystems which support all life. Children will be able to study after dark, hospitals and health clinics will function properly and nations will be more energy secure."
2. The systems approach is essential for infrastructure interrelationships; for example, the energy infrastructure price structure can change the price structure of the transport infrastructure and the building infrastructure and vice versa. The symbiotic dynamics of energy, transport, and building infrastructures within the existing planetary boundaries can be assessed by systems analysis.
3. Population dynamics (growth, urbanization, and aging) can influence the dynamics of energy infrastructure. At IIASA in Laxenburg, researchers use multistate demographic models for forecasting the size and composition of the world population in the year 2050, and the economic effects of different spatial population distribution scenarios such as megacities. The environmental maintenance of the aging society is another major issue.
4. The increased implementation of the sustainability paradigm in the future energy infrastructure might be the best method to decrease the environmental and health problems of this century. The estimated share of the world's nonsustainable energy infrastructure was 84% in 2010. In other words, we have a long way to go to increase the share of sustainable energy infrastructure in the world and minimize energy path dependence (Mansson 1993; IEA 2007; Hochrainer 2009).
5. A new integrated Ministry of Energy and Environment (MEE) should be generated in every nation for low-carbon prosperity. All environment-related questions (taxes, investments, demand management, and other policy variables) will be concentrated in this ministry. Achieving policy coherence among national, regional, and local targets or applying more bottom-up and less top-down perspectives is critical for the energy sector. MEE could achieve better efficiency and efficacy of national energy and environmental policies for a sustainable future (Nordhaus 1995; Silveira 2001; IPCC 2007; MacKay 2010).

The Russell–Einstein Manifesto (1955) is a historical document signed by 10 Nobel laureates for the perils arising from the development of nuclear arms in the Cold War era:

> In the tragic situation which confronts humanity, we feel that scientists should assemble in conference to appraise the perils that have arisen …

We may need a new and revised Russell–Einstein Manifesto and a 'grand unified theory of sustainability' for inspiration and scientific guidance of modern energy and environment–climate complexities.

Notes

1. The definitions of risk and uncertainty are overlapping in the disaster literature.

   Frank Knight's differentiation (1921) of risk and uncertainty in economics has been ignored. According to this theory, risk can be expressed in terms of probabilities in a stochastic decision-making process. On the contrary, uncertainty cannot be expressed in terms of probabilities.

   There is a misperception of risk in terms of underestimation of probability and costs of a disaster. This misperception leads to the lack of interest in mitigation and risk management strategies.
2. Fukushima means 'good luck island' in Japanese. Fukushima Daiichi means 'good luck island number one.' In this

we refer to the Fukushima Daiichi nuclear power plant. There is also a plant called Fukushima Daiini (Fukushima number 2) nearby. Fukushima Daiini did not have any problem with the tsunami.

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3.08 Climate and Energy Production – A Climate Services Perspective

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3.08.1 Introduction

In the energy sector, climate information can play a strategic role, particularly in hot spot regions such as the Mediterranean region. In order to limit GHG emissions, within the European Union (EU) framework there will be opportunities for trading renewable energy quotas among member states and to gain credit for electricity imported from renewable sources in countries outside the EU (Komendantova et al. 2012; Club of Rome 2008, http://www.clubofrome.org/eng/home/). This framework will trigger new, strong interaction between climate information providers and energy sector stakeholders. The basic assumption of this perspective, of course, is that a prediction of climate on multi-decadal time scales is attainable.

Such trades are also envisioned in initiatives such as the Mediterranean Solar Plan (MSP). The goal of the MSP is to generate 20 GW of new power production capacity based on renewable energy (photovoltaic, wind, and CSP (concentrated solar power)) in the Mediterranean by 2020. This will contribute to energy efficiency in the region and states, institutions, firms, and investors from Northern and Southern Europe will be involved in a common industrial project with high potential of economic growth and employment.

An even more ambitious plan for renewable energy, known as the Desertec Industrial Initiative (DII, Knies et al. 2008), was announced by a consortium of German investors in July 2009. The DII has a target of generating €440 billion in investments on CSP in North Africa largely for export to Europe. The Mediterranean energy plan is of paramount importance at the European level in order to transform the EU into a low-carbon economy with strong competition of internal markets and an improvement of supply security and employment prospects. In addition, renewable energy sources will play an important role in responding to climate effects over the region.

For example, enhanced use of solar power could address the increasing energy demand for summer cooling and, along with wind energy, provide the energy source to power desalinization plants needed if the Mediterranean area becomes more arid. The European goals for 2020 include reducing GHG emissions from all primary sources by at least 20% with respect to 1990, increasing the share of renewable energy sources (RES) by 20%, and improving energy efficiency by 20% (the European 20-20-20 target).

How climate information can be useful for specific energy sectors depends on the development of a strong interaction between energy producers, energy managers, and climate experts. This interaction is a fundamental step toward a decarbonized society. The primary goal of climate services for the energy sector is thus to develop a design, research, and communication protocol by which climate information is transferred from the science realm to the stakeholder application realm in order to develop suitable adaptation measures.

The most innovative aspect in the development of this climate services framework will be its bottom-up approach, by which stakeholders are to be involved in the design of the services from its early stages in conjunction and strong communication with the science community and the climate information providers (e.g., national and international climate services centers, meteorological centers).

3.08.2 Climate Services Framework

Increasing the quality, reliability, and detail of climate information for societal use has become a major challenge in regions whose economic growth and social development crucially depend on adaptation to climate variability and longer-term trends. In this regard, the Third World Climate Conference (WCC3) put forward a strong recommendation for the development of a global network of Climate Service centers (Mr. Michel Jarraud, Secretary-General of the World Meteorological Organization – WMO, WCC-3, 2009).

> "by boosting the observations and research we have available for monitoring the climate and then facilitating the creation of sector- and regional-specific products and services that will be readily available to all who need it."

An effective exchange of information between the science and stakeholder communities is especially important for regions that are particularly vulnerable to climate variability and longer-term change. Therefore, more than 2000 scientist

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during the WCC3 conference set up the Global Framework for Climate Services (GFCS) with the aim of strengthening the production, availability, dissemination, and application of prediction of climate science and services. Its objective is the development and provision of scientific information and climate predictions for risk management for adaptation to climate. One challenge, of course is whether skillful predictions of changes in climate statistics on the multi-decadal time scales can be attained. A major requirement for the GFCS should be to assess the predictability of changes in climate statistics on the time and space scales needed by stakeholders.

The GFCS has four main elements. In addition to climate research, observation, and monitoring, the real novelty of this initiative is represented by the mechanism of interaction with users User Interaction Mechanism (UIM) system and the World Climate Services (WCS) system. In fact, the center's mission for the GFCS are increasing and improving interactions between service providers and users of the climate information.

The fisheries, water, health, forestry, transport, tourism, and energy sectors are increasingly concerned with climate risks, but the decision makers involved in these sectors are not always culturally ready to assimilate the available climate information and apply it. The needs of the user community are diverse and complex. A close interaction between scientists and experts from other fields and disciplines is essential to focus on the specific requirements of different users.

Adaptation capacity depends on the structural link between energy sector infrastructures/activities and climate, on the time scale of the climate–energy link, and the development of a strong interaction between climate information providers and energy sector stakeholders. The base time horizon of interest in the energy sector ranges from seasonal to decadal time frames and from present climate information to the entire spectrum on plausible future climate conditions.

This is the time horizon of greatest interest for the assessment of impacts and the development of adaptation measures. It includes the contributions of both natural climate variability (especially in the early decades), GHG-forced climate change (especially in the latter decades), and other human drivers such as land-use change (Pielke et al. 2009; Anav et al. 2010). It will place climate services framework within the newly emerging field of decadal climate prediction, which will allow for the potential of a strong novel contribution. The spatial scale of interest for climate services' framework will be regional (e.g., catchment basin) to local (e.g., city level). This can be achieved through the refinement and development of new dynamic and statistical downscaling tools, although caveats have been highlighted (Pielke and Wilby 2012). We do stress, however, that although the temporal and spatial scales of interest are as stated above, the actual ones will be dictated by the stakeholder needs involved in GFCS framework.

Finally, an important focus of the climate services framework will be on the development of, and provision of training for, a new research expertise lying at the interface between the science results and the stakeholder application. To date, the communication between the science and application communities has been sorely lacking, partially because of the widely different perspectives across them. Even within the Intergovernment Panel on Climate Change (IPCC) process there is still a stark divide between the science (WGI) and the application segments (WGII and WGIII). A new expertise is needed which can more fully integrate the needs and transfer of information between these communities without a preconceived perspective.

3.08.3 Potential Climate Impact on Energy Production

Ernst & Young, in their conceptual framework, place the crossover point between costs and margins for renewable energy in 2012–13 (*Renewable Energy Attractiveness Indices* Issue 27, 2010). In most of the Western countries, renewables are now transitioning from the stimulus to the poststimulus phase. Nevertheless, in recent months the removal of subsidies is balanced by the Fukushima effect. The health of the general economy continues to have a major effect in driving renewable energy. However, climate-related issues begin to have an important role in planning and managing new renewable plants. Here, we summarize key energy sectors in which the use of climate information becomes more and more important. We do not intend to provide a complete listing of sectors and of climate-related parameters, instead we would like to introduce some examples that could be potentially viewed as benchmark case studies (special emphasis on Power Grid as an emerging issue for green energy) in the context of the climate services framework.

Table 1 is a summary point for identifying the needs for climate data in addressing the various fields of application of the energy sectors. To understand the requirements of climate products and services for energy management, one only needs to look at the trends in the analysis of climate information in support of energy activities.

3.08.3.1 Power Grid

Electricity demand is dependent on temperature, owing to the use of residential and industrial HVAC (heating, ventilation, and air conditioning) equipment, refrigeration, and irrigation. During winter or summer periods, a small change of average temperature can lead to a significant variation of electricity load, especially on particularly warm or cold regions. Trends in extreme weather and climate events (e.g., heat waves, storms, snowstorms) will strongly affect these aspects of the power grid. To give an example, Figure 1 describes the relationship between average temperature and average load on a daily basis in Italy; this analysis has been performed using data provided by TERNA, the Italian transmission grid operator, considering the period 2003–09. We can observe how intensively the average temperature affects the electricity demand during the entire year, fitted with a 2nd order polynomial, and then in particular during the summer period when the electricity demand is strongly influenced by the needs of refrigeration and ventilation equipments. Similar behavior is observed on other Mediterranean countries, like Spain and France, with the respective energy demand data (see Valor et al. 2001, for a study on Spanish electricity loads).

For this reason, in order to avoid power outages and the consequent negative impact to customers, it is important to prevent critical situations using a load forecasting model with

Table 1 Basic climate information needs of the energy sector

			Type of climatological input data	
Field of application	*Energy element needed*	*Climatological element needed*	*Time scale*	*Space scale*
Power Grid	Daily load and network structure	Air temperature	d, m	g, a
Gas production and distribution	Network structure	Precipitation	h, d	g, a
		Air temperature	d, m	g, a
		Wind speed	d, m	g, a
Wind	Production – high resolution time series	Wind	h, d	s, g
		Pressure	d, m	s, g
Solar	Production data	Radiation	h, d	s, g
		Wind	min, max	s, g
		Temperature	d, m	s, g
		Humidity	d, m	s, g
		Clouds	h, d	s, g
		Aerosols	h, d	s, g
Hydropower and water-based cooling systems	Production data	Temperature	d, m	s, a
	Plants temperature	Rainfall	d, m	s, a
		Runoff	d, m	s, a
		Water level	d, m	s, a
		Snow cover	d, m	s, a
		Snow melt	d, m	s, a
		Soil Moisture	d, m	s, a
Marine energy	Production data	Wind	d, m	s, g
		Wave height and direction	d, m	s, g
		Current speed	d, m	s, g

s = point values; a = areal values; g = grid values; y = annual values; m = monthly values; d = daily values; h = hourly values; min = minimum values; max = maximum values.

accurate weather models as inputs. An accurate forecast can give precious information both on short (from minutes to days) and long (from weeks to months) time scales, allowing an effective and efficient operations management and power dispatch for electric utilities. Finally, the definition of plausible climate scenarios is of critical importance for planning on both the supply-side (i.e., creation of new power stations, transmission lines expansion, and effect of climate on renewable-energy generation) and the demand-side (i.e., influence of climate on energy demand).

Another aspect that would increase the effects of climate on power grids is the global migration of populations toward

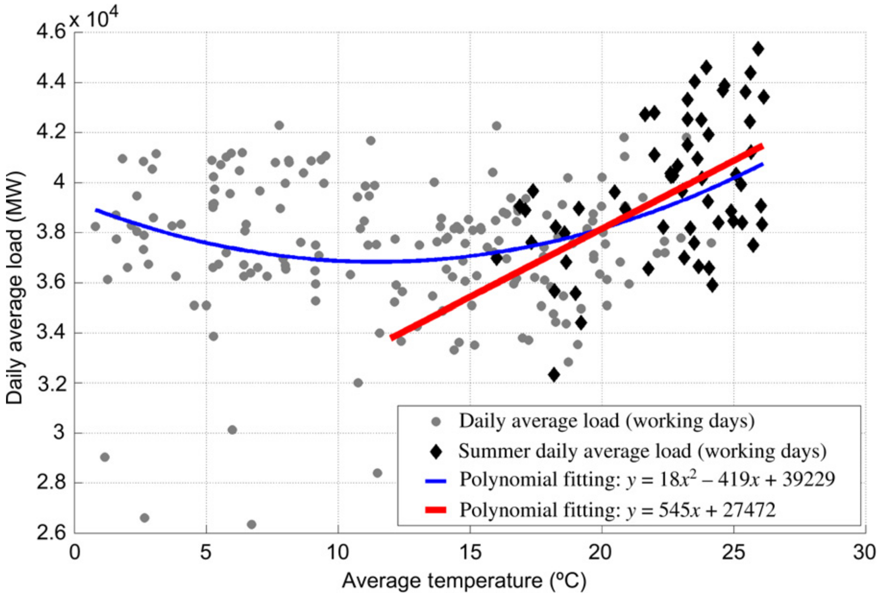

Figure 1 Relationship between air temperature and daily load in Italy during the years 2003–09.

urban areas; in fact by 2040 more than the 60% of world population will live in urban areas (United Nations, Department of Economic and Social Affairs, Population Division 2009). Predicting and providing the electricity demand of larger cities will become more and more important during critical events like heat waves: an example of such an effect has been observed during the 2006 heat wave in North America that caused power outages in many densely populated areas, like Southern California and New York City. Moreover, temperature also affects the operation (and maintenance costs) of high-voltage transmission lines; in fact their operation is strongly affected by extreme weather events (heavy rain, icing, lightning strikes, storms, cold snaps). In the case of interruptions, it is critical for transmission grid operators to balance the grid with different methods: with generation response mechanisms (pumped storage or reserve power stations), asking to the distribution network operators to lower the demand, and using electricity interconnections with neighbor countries.

Another aspect that must be taken into account is the influence of temperature on transmission capacity; in fact the ambient temperature affects the conductors' resistance and, consequently, power losses. Moreover, when a power line heats up for both heavy load and hot weather, it stretches and sags with the possibility to hit nearby objects or vegetation, causing a short circuit and line disconnection.

A discussion about the influence of weather and climate on load forecasting and, more in general, on the energy industry can be quite relevant in vulnerable regions such as the Mediterranean.

3.08.3.2 Gas Production and Distribution

As many winter examples demonstrated, European countries depend on the reliability of eastern and southern gas supply (Russia, Algeria, etc.). Europe is connected to other world regions via pipelines. The length of these pipelines amounts to several thousand kilometers operated under different climate conditions. The global warming increases the probability of extreme events (heavy precipitation, heat waves, wind storms). Climate information is of considerable importance and widely used in the gas industry. Based on the analysis of Russian industry (Troccoli 2010), the natural hazards in the accident rate amount to about 8%. An important component for risk assessment and for the prevention of accidents is the improvement of climate information of the atmospheric extremes, which are used for engineering solutions and protection of facilities.

3.08.3.3 Wind

Wind power has unique characteristics with its output varying greatly and within short periods of time. Wind variability cannot be completely controlled or predicted. Consequently, an increasing wind market share puts pressure on the electricity grid system and its innovative management. It is widely recognized that as the wind market increases, there will be a greater need for compensating sources that can support its irregular character (Vos 2012). This research featured natural gas as the best-suited generation fuel to support an increasing wind market.

With great expectations placed by Germany and the United Kingdom among others, on a significant offshore wind expansion to meet their 2020 targets, and with tens of billions of euros envisaged to build next-generation offshore infrastructures, wind energy would become a viable and reliable part of the energy mix. With high-power wind turbines (up to 5 MW) placed at about 100 m high for marine use, wind information needs to be much more accurate considering all statistical moments of the wind and the shape of distribution that are required. Detailed information at high resolution has a relevant economic value for planning new wind farms. Considering long-term climate trends and variability, changes in atmospheric teleconnection patterns (for instance NAO) would influence the wind statistics of specific regions, such as the Mediterranean, influencing the number and strength of storms, and in turn impacting on renewable-energy production. Therefore, climate is an issue for renewable energy, with respect to the payback period in capital budgeting and insurance planning.

Wind farms could be a very good example and benchmark for evaluating reliability and use of climate information. The availability of wind energy production data and of wind farm models allows us to analyze the link with wind variability. The production of high-resolution wind data down to scale of a wind farm and for a long period, long enough to be used as a statistical reference, is a challenge for the climate services framework. Many climate impact analyses, including those focused on wind energy, use individual climate models and/or statistical downscaling methods rooted in historical observations (Rassmussen et al. 2011).

3.08.3.4 Solar

With over 17 GW installed, Germany leads this market in terms of capacity. Spain has the second highest solar capacity with about 4 GW installed. North African countries have a significant solar potential (around 1700–2200 Kw m^{-2} per annum). The Mediterranean countries are able to support CSP and photovoltaic (PV) plants on a large scale. In the field of PV and CSP, environmental information that is lacking for sound financial assessment and planning concerns the variability of aerosols and dust in the atmosphere. Dust affects production by thin film deposit on mirrors and modules. Aerosols in the atmosphere dramatically affect the productivity of CSP (Murphy 2009), which is based on direct net irradiation (DNI); other parameters, such as dew, frost, and snow, can be also relevant. Both present weather reanalysis products and plausible future changes in these weather variables taking into account aerosols information are relevant for solar planning.

3.08.3.5 Hydropower and Water-Based Cooling Systems

Hydropower is a well-established and mature technology. Three main types of hydro schemes are in use: storage schemes, with a dam impounding water in a reservoir and using turbine(s); run-of-river using natural flow of a river; and pumped storage with two reservoirs for pumping water from the lower to the upper one. All these hydropower plants have a strong dependence on climate in terms of rainfall and temperature. For instance EDF (Électricité de France, the second largest French energy company) analysis suggested a difficult future for hydropower on Pyrenean catchments owing to rainfall shortage, with average energy production reduced by 20% in the period 2015–45 (respect to 1973–2004) and with highly interannual variable hydroclimatic conditions (Fai et al. 2011).

Rainfall is not the unique relevant parameter. The 2003 heat wave in France featured high air temperatures, as well as warmer river water temperatures used for cooling nuclear power plants as a key parameter for plants management. Higher probability of extreme warm events can result in hundreds of million euros in global costs for the energy sector. Energy groups deserve particular attention to climate variability and longer-term trends, and they are developing action plans, including cooling system design modifications, and improved understanding of the impact of climate on facilities.

3.08.3.6 Marine Energy

Concerning the potential of extracting energy from the sea, new technologies are emerging, especially wave and tidal energy extraction. South Korea's first tidal power plant began full operational in 2011; with an output capacity of about 250 MW, it is now the largest in the world. Long-term feasibility studies are looking at about 1 GW capacity in Korea. Ocean currents and waves are the most important parameters to evaluate for these infrastructures. Both have a strong link to the wind and its variability. Climate variability and longer-term trends can affect the distribution and strength of storms, which in turn influence wind and waves variability. High resolution data of ocean currents for a sufficient number of years (10–20) can be very useful for planning new infrastructures.

All these examples show that detailed climate information has a potential economic value in the energy context. Because of decreased feed-in tariff and to a drop-off in loan guarantees, operative margin will decrease, which in turn increases the relevance of detailed climate information in order to maximize production and to reduce excess margin of safety. Therefore, reliable regional and local estimates of trends in climate parameters in the regions of the highest risk (hot spots) will allow enhancing the quality of planning and design work and safe operation of facilities under construction.

A challenge for the future is for the climate community and the energy community to work together to span the temporal and spatial gaps and to define adaptation measures. A first step should be the identification of requirements, defined, for example, by:

- an assessment of the impacts of climate on a set of different types of projects and plans
- development of methods, standards, and procedural guidelines for impact assessment and climate adaptation
- production of guidelines for integrating impact assessments into planning at the local level and triggering a bottom-up approach for climate adaptation

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3.09 Energy Market Fundamentals

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3.09.1 Energy Market Overview

Over the last 15 years, the US electric industry has undergone fundamental changes that have dramatically changed the way power is produced, transported, and consumed. The industry has moved from a cost-based regulation to competitive market structures. The restructuring of the US electric utility industry is the most massive and complicated industrial reorganization ever attempted in the history of the world. In terms of sheer size (i.e., revenues affected), it dwarfs all of the prior industries restructured either in the United States or abroad, whether telephone, natural gas, railroad, airline, or motor carrier. In terms of complexity, it affects the overlapping regulatory jurisdictions of three nations and more than 55 state, provincial, or other governmental agencies, and by all measures it is unprecedented.

The energy markets in the United States are regulated by the Federal Energy Regulatory Commission (FERC), an independent agency administratively housed within the Department of Energy. FERC regulates wholesale electricity rates, approves transmission line projects, and sets transmission rates. However, FERC's authority is limited in important respects:

1. For the most part, FERC's ratemaking and transmission authorization authority is limited to IOUs in the 48 contiguous states outside of ERCOT, Texas. The entities, which eventually formed ERCOT severed nonemergency connections with outside grids in August 1935. Their objective was to avoid falling under the ratemaking jurisdiction of the Federal Power Commission (FERC's predecessor) by maintaining a purely intrastate system. D.C. ties between ERCOT and the Eastern Interconnection were constructed in the 1980s, but these do not put ERCOT under FERC rate jurisdiction due to a specific exemption in the law (Cudahy 1979).
2. While FERC must approve transmission projects proposed by jurisdictional utilities and establishes rates, a project also needs a siting permit from every state the line will traverse.

Another aspect of FERC regulation is its efforts to encourage competition in the electric power market. In 1996, FERC mandated 'open access' to the transmission system (FERC Orders 888 and 889). Open access requires transmission owners to make available, at cost-based or market-based fees, transmission capacity to any generator or power buyer that is or can be connected to the system.

The objective is to prevent transmission owners from using their control of the power system from stifling competition. To further facilitate open access, in 1999 an FERC order encouraged the creation of the Regional Transmission Organization (RTO). Figure 1 illustrates the current RTO in the United States. The RTO can take over operation of the transmission network in a region or large state, although utilities continue to own their systems. The RTO ensures open access to the grid, operates the energy markets, coordinates transmission planning, and establish mechanisms to pay for new transmission lines (FERC Order 2000).

The RTO manages markets for energy, transmission, and ancillary services. From the viewpoint of standard economic theory, wholesale markets for electricity are inherently incomplete and imperfectly competitive. Some incompleteness is inevitable because power is a flow (or field) of energy that cannot be monitored perfectly and storing potential energy is expensive and in massive scale still illusive. Also, flows on transmission lines are constrained continuously by operational limits and environmental factors, and ramping rates of generators are limited due to physical constraints. The primary cause

http://dx.doi.org/10.1016/B978-0-12-384703-4.00318-X

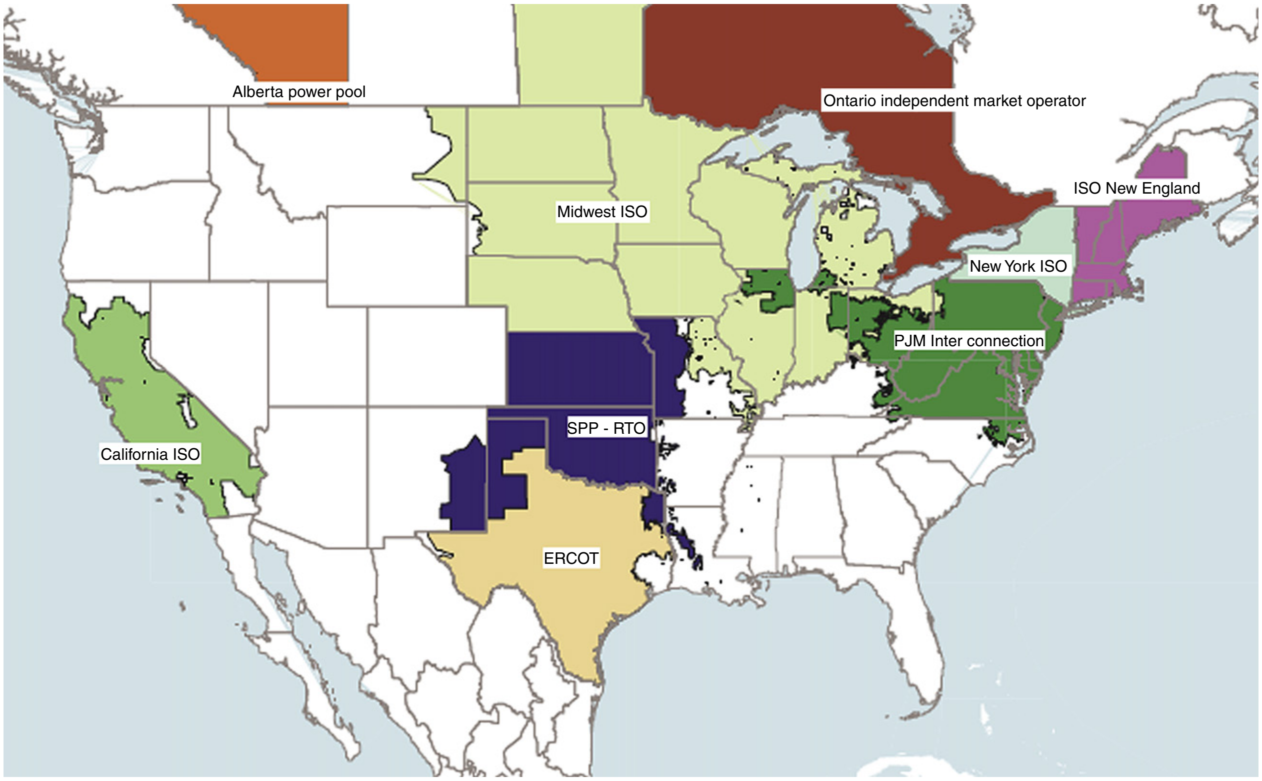

Figure 1 North American Regional Transmission Organization. **Notes:** ERCOT = Electric Reliability Organization of Texas; ISO = Independent System Operator; MISO = Midwest Independent System Operator; SPP = Southwest Power Pool; PJM = Pennsylvania – New Jersey – Maryland Interconnection. The following are regional transmission organizations under the terms of FERC's Order 2000: ISO New England, PJM, Midwest ISO, and SPP RTO. [Available online at http://www.ferc.gov/legal/maj-ord-reg.asp.]

is variable demand that presently is almost unresponsive to spot pricing at the retail level for all, except for large industrial customers. Devices for continual control and metering are feasible. Innovative tariffs and service plans have been introduced on small scales, but implementation was slow before liberalization and paradoxically, often retreated after liberalization. In the long run, imperfect competition in power markets stems from the same factors as in other industries, such as economies of scale and other entry barriers, and oligopolistic ownership. Competition is imperfect in intermediate time frames, because production is capital intensive and construction delays are long compared to variations in supply and demand conditions. Competition is inherently imperfect on short time scales because of technical rigidities and physical constraints on the supply side and the inelastic nature, to a large extent of the demand side.

These problems specifically associated with power require strenuous efforts to muster sufficient generation sources and transmission capacity to supply predicted and then actual demand, supplemented by reserves to meet contingencies. The RTO plays exactly this role. There is presently no standard organization of liberalized wholesale markets for power. Every jurisdiction uses a different structure of regulation, governance, system management, and markets. One way to place these various structures along a single dimension focuses on degrees of reliance on market processes, as compared to managerial discretion. This dimension reflects differences in the extent of unbundling of energy, transmission, and reserve capacity into separately priced commodities, and differences in the priority assigned to enhancing coordination. Along this dimension, the organizational forms span a spectrum between two extremes (Wilson 1998).

One extreme assigns broad authority to the operator, intending to recapture advantages of tight coordination obtained previously from vertical integration. Currently, all the RTOs in the United States follow this market structure. We call this market structure an 'integrated market structure.' The other extreme form is more decentralized, because the operator's responsibility, beyond managing transmission, is to facilitate private markets for other products. For instance, the operator allocates transmission access, but also it auctions tradable transmission rights and ensures joint feasibility of the participants' operating schedules. In this model, separating markets for energy, transmission, and ancillary services sacrifices tight coordination, but intends to maximize the role of private markets. We call this market organization an 'unbundled market structure.' Most of the operators in Europe follow this market organization, with a few exceptions, such as Poland and Greece.

If power market were complete and perfect, both market structures could obtain the same result. This is the primal–dual equivalence of first–best implementations, when vigorous competition makes the first–best incentive compatible. Departures from this equivalence differ for the two designs. Integrated market systems start from the premise that gains will be realized from tight coordination in daily operations, and potentially from longer-term obligations and subsidies aimed at strengthening overall reliability. Unbundled market systems start from the opposite premise that participation is voluntary, with no long-term obligations other than a general tariff approved by the regulator. Competing forward markets are encouraged to the extent feasible. The necessity of a system operator with exclusive authority to manage the public good represented by the transmission system is acknowledged. The operator's responsibilities include real-time operations that protect system reliability, but its authority to intervene in forward markets is limited to cases where prior commitments promote reliability, such as day ahead scheduling of transmission.

3.09.2 Key Energy Market Models

Over the last 15 years, the key elements of liberalized energy market have been developed and implemented in many jurisdictions. They include provisions for competitive wholesale markets for energy, an open-access transmission system managed by a system operator (RTO in the United States or Transmission System Operator (TSO) in Europe), and competitive retail markets, leaving the regulated utilities with responsibilities for distribution and a universal service obligation as the default provider, procuring supplies as needed in wholesale markets.

As we discussed in Section 3.09.1 Energy Market Overview, all the RTOs in the United States follow the 'integrated market structure' model. Specifically, all the RTOs run forward and real-time energy markets, ancillary services, and transmission markets by optimizing a Security Constrained Unit Commitment (SCUC) and a Security Constrained Economic Dispatch (SCED) with Locational Marginal Prices (LMPs) derived from shadow prices on system constraints. On the other hand, the TSOs in Europe follow the 'unbundled market structure' model. Specifically, the TSO allocates transmission, procures reserves, and conducts the real-time balancing market to protect reliability while a separate Power Exchange (PX) manages forward markets for energy–although other market-makers could compete with it. The reliance on clearing a sequence of simple markets is the key ingredient of these unbundled markets. In the remainder of this section, we briefly present the most prevalent energy market architectures currently in operation.

3.09.2.1 The Bilateral Energy Model

The bilateral model is motivated by the concept that free market competition is the best way to achieve competition in an electricity market. In this model, suppliers and consumers independently arrange power transactions with each other according to their own financial terms. Economic efficiency is promoted by consumers choosing the least expensive generators. This model might be an obvious choice if a commodity other than electricity were being traded. The special characteristics of electric power networks introduce two problems that have to be addressed in this model. The first problem relates to the presence of transmission constraints, which requires that there exist some form of coordination to maintain system security and make the most efficient use of the constrained transmission system's capacity. The second problem relates to transmission system losses. The treatment of losses is outside the scope of this chapter, but is generally well understood. Both of these problems may be considered as externalities, which have been internalized in the dispatch process in the past. In addition, other ancillary services must be provided to secure the transfer of power from suppliers to consumers (Singh et al. 1997; Singh and Papalexopoulos 2001). These too are outside the scope of this chapter. The resolution of these problems requires a centralized system operator (RTO or TSO) to manage the transmission grid and ensure the security and reliability of the system.

3.09.2.2 The Pool Energy Model

The pool model is motivated by the concern to accommodate the special characteristics of electric power networks within the electricity trading process. The locational aspects of the pool model can be accommodated using a zonal transmission model (Singh et al. 1998), or detailed nodal transmission representation based on the theory of Nodal spot pricing (Schweppe et al. 1988). This model relies on the actions of a system operator for receiving price and quantity offers from generators and demand, selecting the most efficient sources of supply to satisfy prevailing constraints, and making financial transactions that involve payments from consumers and payments to suppliers. The prices that govern these payments are based on the bids submitted by market participants and adjustments made by the system operator to reflect the locational value of suppliers, in terms of their contribution to system losses and constraints. Both models deploy a SCUC bid-based optimization algorithm to clear the market, but they differ on the level of transmission representation that is part of the optimization. Hybrid architectures that combine key elements of both models are also possible.

In the following two sections, we present the market architectures of the zonal and the nodal models. In Section 3.09.5 Transmission Rights Models, we present the basic design of various alternative transmission rights markets that are required to provide hedging to energy market participants.

3.09.3 The Zonal Energy Market Architecture

3.09.3.1 Introduction

In this section, we present a brief description of the zonal energy market architecture.

The zonal model is a compromise between an unconstrained energy pool and the nodal model, where a detailed transmission network is part of the market clearing. In the case of an unconstrained energy pool, no network model is used. In the zonal model, a zonal network model is necessary. This model can be as simple as having a single equivalent node for each zone, or the next level of complexity, zonal equivalents with a single internal node where all zonal resources are connected. The effect of such a simplified model is that the same energy price applies to all resources in a given zone. The disadvantage of this model is that the outcome ignores the different locational effects that resources have in mitigating congestion. These effects are reflected in the Power Transfer Distribution Factors (PTDFs), that is the sensitivities of transmission flows to power injections (Wood and Wollenberg 1984). If the PTDFs are close for all resources in the same zone, this model is reasonably accurate. If, however, the PTDFs vary greatly within a zone, the resulting schedules are not optimal, and may not even be feasible. Experience gives credence to the claim that in systems with strong interconnections forming loops, a simplified network model is inefficient, and does not ensure feasible schedules. Further, it negatively affects reliability. For these reasons, all RTO markets in the United States have abandoned this market architecture. However, it remains the dominant model in Europe.

Zonal pricing (uniform price within a zone) does not necessarily require a simplified model. Zonal pricing can also be applied using a full network model. The zonal price is calculated as a weighted average price of all nodal prices within the zone. This price is efficient if the price dispersion within the zone is small, which, in turn, depends on the dispersion of PTDF within the zone. Again, in looped systems, price dispersion may be large, hence the zonal pricing is inefficient and leads to incorrect and skewed pricing signals.

Obviously, irrespective of the detail of the network model used in the forward markets, real-time dispatch requires a full network model. The necessity is dictated by operational considerations that require a feasible dispatch. Furthermore, efficient prices that correspond to an optimal dispatch are very important in real-time since they set incentives for proper behavior by market participants. This creates another serious problem for the zonal model, i.e., the inconsistent network models used by the forward and the real-time market. These inconsistencies can be extensively manipulated by the market participants to the detriment of the customers and the market as a whole, as clearly the energy crisis in California demonstrated. A comprehensive analysis of the problems associated with the zonal model is presented in Alaywan et al. (2004).

3.09.3.2 Zonal Energy Market Architecture Modeling

In the zonal model, the transmission network is divided in zones. Congestion between zones is managed through market mechanisms (interzonal congestion) and congestion within zones is managed like in the old environment, and the costs are spread to all customers within the zone. The assumption is that congestion within the zones is infrequent and it is sufficient to be priced on an average cost basis. This means that financial rights within the zones will be difficult to auction and to resell in a secondary market. Congestion between zones, on the other hand, is frequent and marginal cost pricing is deployed to promote its efficient use.

The objective of the interzonal congestion management optimization problem is to minimize the net cost of redispatch, as determined by the market participants' submitted incremental and decremental price bids. This objective function is equivalent to the net power generation cost objective used in conventional Optimal Power Flow (OPF) applications. The control variables in the interzonal congestion management optimization problem are the market participants' generator outputs in all congestion zones. For each generator, a set of generation quantities with associated adjustment incremental or decremental energy bids are submitted by the market participants for congestion management. Adjustable loads with demand-side bids can also be used as controls. Each market participant's adjustment incremental and decremental bids, and demand-side bids across zones, constitute an implicit bid for transmission.

The constraints in the interzonal congestion management optimization problem, besides limits on control variables, are the nodal active power flow balance equations and the interzonal interface active power flow inequality constraints. Intrazonal constraints are ignored. In some markets, for example the old California energy market, an additional set of constraints, not applicable in conventional OPFs, are added to the problem formulation to enforce market separation between market participants. These constraints enforce the condition that each market participant's net generation matches its net load. These constraints need to be formulated for all but one market participant, the latter being referred to as the 'reference market participant.' (The market separation and nodal power balance constraints will force the reference market participant's portfolio to be balanced at the solution without explicitly formulating a constraint for it.). The principle for enforcing these constraints is to ensure that the system operator does not intervene into the private markets of market participants.

A linear DC–OPF formulation is used, both for simplicity, and for reliable, robust marginal cost calculation. Power system losses are taken into account by dispatching effective power generation, which is the actual generation multiplied by the location-specific generator meter multiplier, which is derived by the location's penalty factor. A full network model, albeit lossless, is used for the system operator's control area. The interzonal congestion management optimization incorporates a linear power flow model. This model can be derived as the usual DC power flow formulation from the AC real power flow equations, by assuming negligible line resistances and small voltage angle differences, as presented in Section 3.15.2 Transmission Grid Modeling of the accompanying chapter 'Transmission Grid Fundamentals.' In this case, the active power balance equations in [17] of Section 3.15.2 can be written as the DC power flow equations as follows:

$$P = [B'] \times \theta \qquad [1]$$

The interzonal power flow constraints are linearized in a similar fashion. Linear power flow equations and constraints are also derived by linearizing the power flow equations and flow constraints about a point. The interzonal congestion management optimization problem is in Linear Programming (LP) formulation, as follows:

$$\min \sum_{l=1}^{L} \sum_{i=1}^{N} c_{l,i} \Delta P_{l,i} \qquad [2]$$

$$\begin{aligned}
&s.t.\ B'\Delta\theta = \Delta P \\
&F\theta \le Pf\max \\
&P_{l,i\min} \le P_{l,i} \le P_{l,i\max}\ \forall l = 1,2,\ldots,L; i = 1,2,\ldots,N \\
&\sum_{i=1}^{N} \Delta P_{l,i} = 0\ \forall l = 1,2,\ldots,L-1
\end{aligned}$$

where

l: Market participant index; i: node index; c: inc. bid;
θ: voltage phase vector,

$\Delta\theta$: change in voltage phase vector from preferred schedule,
P: nodal power injection vector
ΔP: change in nodal power injection vector from preferred
B': linearized Jacobian; F: branch power flow coefficient matrix
$Pf\text{max}$: branch power flow limit vector

At the optimal solution, the usage of congested transmission interfaces will be allocated to the market participants who most highly value the use of these interfaces. This is determined by the implicit value the market participants place on the interfaces through their adjustment incremental–decremental price bids, and the effectiveness of their resources in using the interfaces. The effectiveness of each resource depends on the particular location of the resource in the network. The market participants, which use the congested interfaces, pay for their usage of those interfaces. The schedules of market participants that are not allocating the usage of congested interzonal interfaces are adjusted so that they do not use the congested interfaces. In the case of insufficient resources or demand-side bids in a zone, some load may not be scheduled in the current forward market.

Market participants whose interzonal schedules are partially modified so that they still use some of a congested path are referred to as the 'marginal users' of congested interzonal interfaces, and they set the marginal price on that congested interface according to the implicit value they place on it through their adjustment incremental and decremental bids on each side of the congestion. Market participants with comparable effectiveness, but lower implicit value on an interface, are not allocated usage of the interface. Market participants for which the adjustment range is exhausted or do not supply bids become price takers on the congested paths.

The OPF solution provides all of the marginal cost information that the system operator needs in order to price usage of the congested interzonal interfaces. The system operator will charge each market participant for its usage of congested interzonal interfaces. Each market participant will see a uniform price for transporting power from one zone to another, irrespective of the particular location of its resources within congested zones.

3.09.3.3 Summary

Actual experience with the Zonal energy model in the United States has not been positive. The use of uplift payments to manage the congestion charges within zones can only work as long as the uplift charges remain small. However, as these 'socialized' charges for intrazonal congestion increase, all market participants must pay the charges, without regard to which transactions are contributing the most to the congestion. Since the socialization of the congestion costs creates no incentive to alleviate the congestion problem, the condition will not be alleviated through market mechanisms and it may worsen over time. In fact, averaging congestion charges across all market participants may actually create incentives to cause congestion in some areas, because users of the transmission grid will not see the true cost of their deliveries. Inevitably, the system operator will be required to intervene in order to maintain the security of grid operations. Actual experience has shown that the cost of this intervention can be very significant.

The fall back plan of creating additional zones to manage evolving congestion has also been very problematic. The new congested paths interact with existing long-term transmission rights on other paths, defining new transmission rights that respect existing contracts. In this situation, the zonal energy model becomes complex as the system operator must find a way to define new zone boundaries that solve the evolving congestion problem, in such a way, as to respect the existing transmission rights. As each new constrained boundary evolves, the congestion management problem becomes more complex, due to the interaction of new constraints on the existing physical zone boundaries. These complications create conditions that render the viability of the zonal energy model, its stated objectives of simplicity, and commercial efficiency questionable.

3.09.4 The Nodal Energy Market Architecture

3.09.4.1 Introduction

In this section, we present a brief description of the nodal energy market architecture.

The transition from a zonal to a nodal model in many jurisdictions has become a necessity, because of serious flaws of the zonal model. Actual experience strongly indicates that the zonal model creates inefficient incentives for locating new generation. Further, as we discussed in the previous section, several hidden complications of zonal pricing can be found from England to the old California model, with different ad hoc rules applied to create more and more complex structures to fight against the choices of market participants confronted with administrative prices. The real impact of zonal pricing is to create more administrative rules, poorer incentives for investment, demands to pay generators not to generate power, and proposals to 'socialize' the higher costs by using the taxing power of the system operator. Other problems include inefficient intrazonal congestion, infeasible forward market schedules, socialization of constraint mitigation cost, and lack of demand response.

As we mentioned earlier, the zonal model allows for substantial simplifications in the incorporation of the transmission grid in the market clearing. The rationale for these simplifications is that the differences between the commercial schedules and settlements, relative to the actual schedules required for maintaining reliability, could be resolved without significantly affecting the underlying incentives. The outcome of these design principles was that commercial schedules in the forward market are inconsistent with real-time requirements and operational constraints. In turn, this creates inefficient incentives for market participants and exacerbates any problems arising from the exercise of market power. The resulting incentives create the need for a system of rules and side payments that eliminate the presumed simplicity of the commercial model, both for short-run operations and long-term investment.

The nodal model aims to restore the consistency between the commercial model and the physical reality and between the forward and the real-time markets. The key elements of the nodal market include a bid-based, Security Constrained Unit Commitment (SCUC) for clearing forward markets with simultaneous optimization of energy and ancillary services, a Security Constrained Economic Dispatch (SCED) for clearing real-time markets, locational marginal prices, bilateral schedules, Financial Transmission Rights (FTRs) (see Section 3.09.5.3 Financial Transmission Rights Model), a consistent network model for commercial transactions recognizing actual physical conditions, and a multi-settlement system.

These market elements enhance reliability, better protect wholesale customers from volatility and gaming, incorporate price responsive demand in the markets, and encourage development of new resources, including Renewable Energy Resources (RESs).

3.09.4.2 Nodal Energy Market Architecture Modeling

The nodal market clearing problem includes next-day generation offers, demand bids, and bilateral transactions schedules. The objective of the problem is to minimize costs subject to all system resource and transmission constraints. Similar formulation is used to solve the real-time market problem. In all cases, the SCUC accepts data that define bids (i.e., generator constraints, generator costs, and costs for other resources) and the physical system (i.e., load forecast, reserve requirements, and the security constraints). The SCUC selects resources based on minimum cost, as reflected on bid prices and on physical deliverability by the transmission system.

The SCUC problem has long been viewed as a very complex and intractable optimization problem. One of the most popular methods for solving the SCUC problem has been the so-called Lagrangian Relaxation (LR) method. The accuracy of LR method was considered sufficient for industrial applications before the emergence of wholesale competitive energy markets. However, the development of competitive energy markets, where multiple generation owners compete to provide their products, has increased the pressure for more accurate unit commitment solutions. An alternative approach to LR based method that effectively addresses the new modeling requirements imposed by the system operator markets is based on Mixed Integer Programming (MIP) implementations. The classical MIP implementation utilizes cutting plane and branch and bound schemes. This method attempts to perform an implicit enumeration of all combinations of integer variables to locate the optimal solution. In theory, the MIP is the only method that can make this claim. It can, in fact, solve nonconvex problems with multiple local minima (Guan et al. 2003).

The framework of nodal model pricing was first proposed by Schweppe et al. (1988) and further developed by Hogan (1992). The nodal prices are typically calculated as dual variables or Lagrange multipliers from Optimal Power Flow (OPF) calculations performed to compute the optimal dispatch (Venkatesh et al. 1992). As far as characterization, in terms of auctions is concerned, nodal pricing may be viewed as inherently discriminatory, as different generators are paid different prices. In general terms, the optimal dispatch problem in this case can be set up as follows:

$$\min c(p) + c_N(p_N) \qquad [3]$$

subject to

$$H \cdot p \leq z^{\max} \qquad [4]$$

$$e^T \cdot p + p_N = 0 \qquad [5]$$

where p denotes a $(N-1) \times 1$ nodal power injection vector (excluding the reference bus) and H denotes the transfer admittance matrix (dimension $M \times (N-1)$) that relates the nodal power injections to branch power flows . e is a $(N-1) \times 1$ vector of all ones, $z^{\max}$ is the $M \times 1$ vector of power flow limits and c_i is the net cost–benefit function at bus i.

The Lagrangian for this optimization problem can be written as

$$L = \sum_i c_i(p_i) - \lambda\left(e^T \cdot p + p_N\right) - \mu^T\left(H \cdot p - z^{\max}\right) \qquad [6]$$

Differentiating the Lagrangian with respect to the power injections gives the nodal prices:

$$c'_N = \lambda = (\text{Nodal price at } N) \qquad [7]$$

$$c' = \lambda \cdot e + \mu^T H = (\text{Nodal prices at all other nodes}) \qquad [8]$$

Additional optimality conditions include the binding equalities from (4), the power balance constraint (8), and the complementarity conditions:

$$\mu_j \left(\sum_{k=1}^{N-1} h_{jk} p_k - z_k^{\max} \right) = 0 \forall j, \quad \mu_j \leq 0 \qquad [9]$$

Thus, in the absence of binding inequality constraints, all nodal prices are equal to λ. In the presence of binding constraints, the nodal price at the reference bus N is equal to λ, while the nodal prices at all other buses vary according to sensitivities of the network flow constraints (4) and the relative contribution of power injections at those buses to the congested lines.

3.09.4.3 Summary

All the energy markets in the United States have adopted the nodal energy market architecture paradigm. In this model, since the trading hubs and zones are based on mathematical aggregates rather than physical boundaries, there is not a requirement for the system operator to predict how current flow patterns on the transmission grid will change over time. As new areas of congestion develop with changing flow patterns, the aggregated nodal prices will reflect the changing system conditions, and market forces will decide how transmission reservations are valued over time. This market-based approach does not require the system operator to intervene in the marketplace by taking away old rights and defining new ones as conditions change. In effect, the market will decide which rights are valuable given the current system conditions.

As experience has shown, this design also supports efficient transmission grid operations. As conditions change, the market may define new trading hubs or zones, without the need to redefine existing ones. Since the congestion pricing reflects the actual congestion problems that are occurring on the transmission grid on a continuous basis, the market will find the most efficient solutions to congestion problems as they occur.

The result is reduced intervention in the market by the system operator and lower overall cost to manage the congestion problem. Furthermore, since with this design energy market outcomes reflect actual operating conditions, the nodal energy market offers substantial flexibility to market participants to create financial products that are separate from the physical market. If traders desire to trade only at the hubs or zones, they can do so at their discretion. They can acquire FTRs at the locations of their choosing (i.e., nodes, hubs, or zones) to develop FTR strategies to manage their exposure. Therefore, liquidity is not an issue, as the detractors of this market architecture usually claim (Ott 2003).

3.09.5 Transmission Rights Models

3.09.5.1 Introduction

The basic alternative types of transmission rights in the electricity market differ in the type of proposed property rights, how the rights are specified and measured, what type of financial instruments are involved, and other features, such as details about the design of primary and secondary markets.

Several types of property rights could be associated with transmission network access. A fundamental distinction is between financial and physical rights. Financial rights are rights to revenues associated with transmission congestion. They are conceived as purely financial instruments that have no direct effect on physical flows, but are used to hedge congestion costs associated with energy transactions or held for speculative purposes. In contrast, physical rights are rights to use transmission capacity. A physical right is a right to flow power over a transmission element or a set of transmission elements. In the case of physical rights, a mandatory release mechanism is always required, so that the holder of a physical right may not withhold that right from other users when it is not being used. There are some transmission rights that incorporate elements of both financial and physical rights.

In this section, we describe the most prevalent transmission right models: the Physical Transmission Rights (PTR) model and the Financial Transmission Rights (FTR) model. The FTR model could be based on a flow-gate model, or a point-to-point FTR model.

3.09.5.2 Physical Transmission Rights Model

A physical right is a right to flow power over a transmission element or a set of transmission elements. System operators hold yearly, monthly, and daily interconnection rights auctions to sell transmission capacity to market participants. Market participants may acquire interconnection rights either directly by participating in interconnection rights auctions or through interconnection right transfers. PTRs provide scheduling rights to market participants that are PTR holders.

PTRs allocated through yearly and monthly auctions or resulting from PTR transfers may be transferred by a transferor to a beneficiary. PTRs allocated through yearly auctions or resulting from PTR transfers may be totally or partially resold at the monthly and daily auctions. PTRs allocated through monthly auctions or resulting from PTR transfers may be totally or partially resold at daily auctions. These instruments are prevalent in the European energy markets.

3.09.5.3 Financial Transmission Rights Model

Financial rights are conceived as purely financial instruments that have no direct effect on physical flows, but are used to hedge congestion costs associated with energy transactions or held for speculative purposes (Treinen and Papalexopoulos 2002; 2005; Hogan 2002; Oren 1997). FTRs can be point-to-point or flow-gate rights, i.e., rights on specific paths. FTRs, also called Congestion Revenue Rights (CRRs) or Transmission Congestion Contracts (TCCs), have been implemented in all energy markets in the United States FTRs can be configured from node-to-node in the system or between aggregations of nodes, called hubs. Hubs are determined by the frequency and importance of commercial transactions, and they may be used instead of individual nodes to facilitate trading, and increase liquidity in the secondary markets. The energy price at a hub is usually determined as the load-weighted average price of all nodes comprising the hub.

A point-to-point transmission right can be further defined as either a forward (obligation) contract or an option contract. A forward financial contract from point A to point B in the network, pays its holder the energy price difference between B and A (price at B minus price at A), which can be negative at times. The forward contract is a perfect hedge if the holder schedules its right fully, since the contract payment or charge offsets completely the congestion charge or payment for using the transmission path. If the holder does not schedule the right, the contract may result in a payment, if the right is in the direction of congestion, or in a charge, if it is in the counter flow direction. In the first case, the payment is collected from other users of the transmission system, who in effect rent the right to use the transmission path from the holder. In the latter case, the charge represents the cost of the congestion that the holder causes by not scheduling the counter-flow energy, and it is used to pay holders of forward rights in the opposite direction.

An option contract gives the holder the right, but not the obligation, to exercise the contract; that is, the holder is only paid if there is congestion in the direction of the right, but never pays if congestion is in the opposite direction. Both flow-gate rights and point-to-point rights can be specified as either forwards or options.

Forwards and options require slightly different formulations for the auction of transmission rights. In the general case, the auction takes the form of an optimization model that selects transmission bids to maximize transmission revenue without exceeding the capacity of the transmission network. For forwards, the use of the transmission network is maximized by allowing counter flows. For options, the effect of counter flows is ignored by constraining the transactions to the physical capabilities of the network.

Flow-gate transmission rights are usually associated with proposals for decentralized (forward) wholesale electricity markets and the zonal energy model. On the other hand, point-to-point financial transmission rights (PTP FTRs) are usually associated with centralized, mandatory, or voluntary pools with a nodal architecture organization.

All FTRs outstanding at a given time must be simultaneously feasible. In other words, the transmission system under security constrained conditions must be able to accommodate all the potential energy flows represented by an outstanding set of FTRs. Simultaneous feasibility is initially determined in the distribution (auction or allocation) process and reconfirmed in subsequent distributions. The system operator ensures simultaneous feasibility by executing a Simultaneous Feasibility Test (SFT). Bids that are not simultaneously feasible are reduced in accordance with the FTR auction optimization formulation.

PTP FTRs have some desirable properties for the system as a whole, with the quantity of FTRs limited to the simultaneous capacity of the network. Two properties of such FTRs are particularly important:

- Revenue Adequacy: The congestion rentals accruing to the pool are adequate to make FTR payments, even when the dispatch and the flows on particular lines change assuming that all the FTRs awarded are simultaneously feasible (Hogan 1992).
- Commercial Protection: The FTRs can fully hedge against price changes between nodes for a fixed number of MW.

3.09.5.4 The Flow-Gate Model

A flow-gate may be defined as a physical transmission interface within the transmission system on which a limit is enforced by the system operator, because its operating condition is perceived to be critical to maintaining reliability and security of the power system as a whole. The interface could be a single element, such as a line or transformer or a set of elements. The limit is typically a specification of the maximum power flow allowed on the element and may be derived from thermal, stability, or other considerations. 'Commercially significant' flow-gates (CSFs) are determined from the set of the flow-gates in the system based on a threshold level of significance, typically the level of the congestion costs incurred in the flow-gates. Note that flow-gates are directional elements; that is the limits and rights on a given flow-gate are different in each direction, or they may be relevant in one direction only.

Sets of buses separated by commercially significant flow-gates and having similar shift factors or Power Transfer Distribution Factors (PTDFs) can be aggregated into zones. A key step in this exercise is the identification of CSFs. One approach is to designate every congested interface on the system as a CSF. Unfortunately, this can produce a very large number of CSFs and zones, resulting in increased complexity without a corresponding increase in the efficiency of the market. A more appropriate approach would seek to select CSFs in a manner that captures the majority of the system congestion, but not necessarily all of it. A suitable threshold (i.e., between 80 and 90%) may be selected. The measure of congestion in such a test should be the dollar value associated with the congestion, as opposed to the number of hours. This would imply that a constraint on a major interface for a few hours might be selected as a CSF before a constraint on a small interface congested for a larger number of hours.

There are two approaches that may be followed to perform such an exercise. The first is to use historical data, if available, and the second is to perform a simulation of the system for several years by deploying a Security Constrained Unit Commitment (SCUC) algorithm. In both approaches, the result will be a ranking by congestion costs of all transmission flow-gates, which can include lines, transformers, tie-lines, interfaces, and contingencies. Any contingency in the output of the model should be aggregated by the limiting element in order to determine the commercial value of the associated flow-gate.

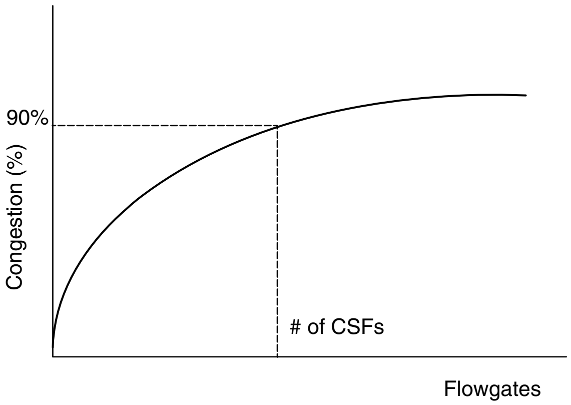

Figure 2 Commercially significant flow-gate identification.

The shadow prices for the binding constraints would yield a measure of the forecasted congestion costs. The congested interfaces would be ranked according to the congestion costs and a graph such as that shown in Figure 2 would be obtained. The graph depicts the congestion cost captured by a given number of flow-gates. Depending on the threshold selected, the designation of CSFs would be derived from the graph.

After the CSFs are determined, appropriate constraints on their directional power flow would augment the congestion management optimization problem. The solution to that problem, irrespective of the particular formulation and the level of detail employed in the network model, would yield marginal prices for the use of congested flow-gates. Market participants would then be charged or paid the marginal price for their scheduled use of congested flow-gates in the direction of congestion, or in the counter flow direction, respectively. The scheduled use of a given flow-gate by a market participant would be calculated by applying the relevant PTDF to that participant's supply and demand schedules. The congestion revenue collected from the flow-gate usage charges would be paid to the flow-gate right holders that acquire these rights in long-term flow-gate transmission capacity auctions. In this respect, the flow-gate rights provide a hedge against transmission congestion costs.

Proponents of the flow-gate model have argued that flow-gates and FTRs can provide a hedge against congestion charges however, since FTRs are subject to simultaneous feasibility and have limited liquidity (Chao and Peck 1996). Experience over the last 10 years, however, dispels this notion. In fact, the flow-gate model suffers from the same problems as the zonal energy model (see Section 3.09.4). Obviously, if congestion costs not accounted for by flow-gates increases, the market inefficiencies also increase. The serious issue of new congestion is also relevant in this debate. Similarly, since interface limits change almost continually, it is unclear what limits the system operator will deploy. Inevitably, these problems require serious interventions by the system operation and a very conservative approach leading to inefficient use of the transmission grid.

3.09.6 Energy Markets Trends

In this chapter, we present a brief exposition of energy market trends that are currently emerging and are expected to dominate the debate on energy markets in the future. This exposition will touch upon overarching challenges that are expected to affect the evolution, format, and configuration of the future energy market design in various jurisdictions.

The overall energy picture is vastly complicated today by the inescapable linkages between energy production and use and the environment. In particular, the risk of climate effects from emissions released by fossil fuel combustion will exert a profound influence on the world's energy options and choices over the decades ahead. It is widely accepted today that energy markets are not only vulnerable to the security of supply and price fluctuations, but also to weather and climate. Extreme weather events affect energy markets in various ways. For example, extended cold outbreaks or heat waves always lead in excessive electricity and/or fuel consumption, and therefore, to scarcity conditions and price spikes. Long-term climate variability may lead to population movements, and therefore, changes in energy consumption and the local energy markets. In addition, energy markets in arid and semiarid zones are more vulnerable to climate, because the variability is larger in these zones and sometimes is associated with the water budget. In this context, the old notion of energy security acquires new dimensions. Reliable access to the energy resources needed to support a healthy economy remains the core imperative, but in the twenty-first century energy security also means reducing the macroeconomic vulnerabilities inherent in the current geopolitical distribution of supply and demand and coming to grips with the environmental impacts of the current energy system.

A consensus is emerging for dealing with this very intractable problem by deploying a mandatory, economy-wide tradable permits system for limiting emissions of carbon dioxide and other greenhouse gases. At the same time, focus is placed for substantially improving energy efficiency and demand response throughout the economy (i.e., in buildings, equipment, industry, and transportation) and, at the same time, promoting energy supply options that advance a number of cross-cutting policy objectives, from reducing exposure to resource constraints and supply disruptions to reducing climate risks.

These policies should be designed to ensure adequate supplies of natural gas and to promote the expanded deployment of low-carbon energy alternatives–including advanced coal technologies with carbon sequestration, next-generation nuclear technology, and renewable sources for electricity production and transportation fuels. Further, these policies need to address siting of critical infrastructure, protect key energy facilities from terrorist attack, and improve the performance and reliability of the electricity system.

With respect to energy efficiency, it is important to focus on some myths related to this important resource. Clearly, no one doubts that increasing energy efficiency or reducing energy intensity (i.e., the energy needed to produce a given amount of GDP) is a key to economic growth. Without the relentless pursuit of energy efficiency, we would need much more energy to produce the same amount of wealth–and we would be producing a whole lot more emissions.

The obvious benefits of energy efficiency have led some people, however, to believe that energy efficiency can solve all our energy and climate problems. However, this is not true. First of all, there is the old Jevons Paradox, named after the nineteenth century British economist, Stanley Jevons, who pointed out that cheaper energy tends to lead to higher energy consumption, offsetting the gains of energy efficiency. This argument is generally accepted among economists. But there is another point to consider about energy efficiency, less well understood, which is that there are different types of energy efficiency measures that have different effects on carbon emissions. There are energy efficiency measures that do indeed reduce carbon emissions, but there are other measures that, unfortunately, have the opposite effect–they lead to higher carbon emissions.

A clear growth supply resource that has a major positive impact on the environment is renewable resources. Renewable energy already plays an important role in the energy supply of many countries today, primarily in the form of hydropower for electricity production and corn-based ethanol, as a transportation fuel. Other renewable options including wind, solar, and advanced biomass technologies for power generation, together with alternative transportation fuels from woody or fibrous (cellulosic) biomass and organic wastes, have made considerable progress in recent years, but still face substantial cost or technology hurdles, as well as, and in some cases, siting challenges. The massive penetration of renewables in certain regions is already distorting the energy markets, however, due to their intermittency and the subsidies they still enjoy, and their collective effect creates a very stressful market and system conditions. Current energy market design configurations need to be modified to be able to accommodate the massive penetration of renewables that is expected to change the energy mix in many regions worldwide.

Another major energy market development that is currently underway is the natural gas revolution. The natural gas market has recently been transformed by the rapid expansion of shale gas production. In 2008, the rise in oil prices was accompanied, and partly fueled, by a belief that an era of permanent scarcity was at hand. This mentality had deep roots extending back to the 1970s, when the United States went from being a minor importer of oil to a major importer. Falling oil output was considered simply inevitable. The only questions were at what rate petroleum imports would rise and whether that rate would be slowed. The outlook was much the same for natural gas. Production would inevitably decline. In the United States, the projection was that the country was on the way to spending \$100 billion a year to import liquefied natural gas from West Africa, the Middle East, and even Australia and Russia. The energy burden on the trade deficit would only increase, adding to the economic distress.

But that is not at all how things are turning out. Technology made the difference. A dozen years ago, shale gas amounted to only about 2% of US production. Today, it is 37% and rising. Natural gas is in such ample supply that its price has tanked.

This unanticipated abundance has ignited a new political argument about liquefied natural gas–not about how much the United States will import, but rather how much it should export. The oil story is also being rewritten. Net petroleum imports have fallen from 60% of total consumption in 2005 to 42% today. Part of the reason is on the demand side. The improving gasoline efficiency of cars will eventually reduce oil demand in the United States by at least a couple of million barrels per day.

The other part is the supply side–the turnaround in US oil production, which has risen 25% since 2008. It could increase by 600 000 barrels per day this year. The biggest part of the increase is coming from what has become the 'new thing' in energy–tight oil. That is the term for oil produced from tight rock formations, with the same technology used to produce shale gas. Tight oil is redrawing the map of North American oil. At the beginning of this year, North Dakota overtook California as the nation's third largest oil producing state. It did not stop there. It just overtook Alaska, to become number 2 after Texas. Tight oil could reach more than four million barrels per day by 2020. What really brings home the new reality is a milestone attained last year. In 2011, the United States registered the largest increase in oil production of any country outside of OPEC. If one takes a broader North American perspective, the changes in the supply picture are even more striking. The output of Canadian oil sands has tripled since 2000, and is now greater than Libya's output before its civil war began in February 2011. With oil demand in the United States declining, output rising and increasing integration with Canada, the United States is certainly on the way to becoming 'energy less dependent.'

As a result of these developments, coal power plants could replace natural gas power plants as the marginal generating units in clearing the auction-based energy market in many jurisdictions. Further, the dramatic increase in conventional generation production puts additional pressure on the renewable energy resources to achieve via technological improvements 'grid parity' and compete on merit in the marketplace without the subsidies and the preferential treatment that are currently in place in most jurisdictions.

Finally, a key factor, which has the potential to have a major impact on future energy trends is the consumer. After all, the consumer is supposed to be king in the free energy marketplace. Energy users are free to decide what kind of energy they will buy and from whom. Our energy markets are not only in a transition to a low-carbon energy supply, they are also still in a transition to free energy markets in most jurisdictions. What we may expect to happen is that although much is still being decided 'from the top,' consumers will more and more assert themselves. This will have far-reaching consequences for the structure of our energy markets.

For example, in Germany, Europe's biggest energy market, there is a battle going on between suppliers of 'green' and 'gray' energy, not only in political circles, but also among consumers. Nuclear power also got into the crossfire after Fukushima, when many German consumers decided to abandon suppliers with nuclear power in their portfolio. This skirmish was prematurely ended when the German government pulled the plug on nuclear power, but in other European countries the battle over nuclear power may well be decided in the end by the consumer rather than by those who think they know best concerning what type of energy is good for society.

3.09.7 Conclusion

In this chapter, we presented an overview of the energy markets including the role of the system operator and the advantages and disadvantages of the two basic market architectures currently in operation worldwide–the integrated and the unbundled market structures. We presented the bilateral market model, which is motivated by the concept that free market competition is the best way to achieve competition in an electricity market, and the pool market model which is motivated by the concern to accommodate the special characteristics of electric power networks within the electricity market trading process.

Finally, we focused on the presentation of the basic design of the most prevalent energy market models that are based on the integrated market architecture–the zonal and nodal energy market models. The key difference between the two is the granularity of the transmission representation in the energy market clearing. Specifically, in the zonal model only few key transmission constraints are represented in the clearing, while in the nodal model a detailed transmission model is present, giving rise to Locational Marginal Prices. The majority of the transmission constraints in the zonal model are not visible in the market clearing process. This means that congestion within zones (i.e., areas within which congestion management is performed outside the market) is socialized. The use of uplift payments to manage the congestion charges within zones can only work as long as the uplift charges remain small, which is not usually the case, at least in system with substantial transmission bottlenecks. As a result, the transition from a zonal to a nodal model in many jurisdictions has become a necessity, because of the serious flaws of the zonal model.

We also presented the basic design of various transmission rights markets that are required to provide hedging to energy market participants–the physical transmission right model, the financial transmission rights model, and the flow-gates model. The most successful architecture is the financial transmission model, which is the predominant model in the United States.

Finally, we presented a brief exposition of energy market trends that are currently emerging and are expected to dominate the debate on energy markets in the future. This exposition touched upon overarching challenges that are expected to affect the evolution, format, and configuration of the future energy market design in various jurisdictions.

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3.10 Energy Networks

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Glossary

Distribution network The medium or low voltage networks used to distribute electricity at lower distances from the suburbs to the end-users; usually on wooden poles.

Interruption No provision of electricity or natural gas to end-users.

Outage Nonoperation of an element due to either breakdown or maintenance.

Pipeline Construction that carries significant amount of natural gas. The diameter changes with the capacity.

Substation Facility changing the level of voltage to lower or higher levels in AC networks.

Transformer Device which changes the amplitude of voltage in alternating currents (AC).

Transmission network The high voltage (above 30 kV) network used to transfer significant quantities of electricity from generators to the suburbs of a city; usually on steel towers.

3.10.1 Introduction

Energy networks are an indisputable part of the energy infrastructure making energy services accessible to increasing parts of global population. Natural gas or oil pipelines aim at delivering fuels to end-users, whereas electricity interconnectors and lines deliver electricity from production sources to consumption nodes. All energy services depend on the efficient functionality of respective energy networks, thus the latter's vulnerability to external factors is of great importance to the consumer's utility.

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In particular, electricity networks (i.e., transmission and distribution (T&D)) are the backbone of power systems. Their mission is to transfer the electricity produced to final customers, safely and reliably, at high power quality and as efficiently as possible. The cost of electricity networks represents a high share of total energy infrastructure costs and is susceptible to rising prices of copper and aluminum, the main materials used for T&D networks. The existing power system infrastructure in the United States is valued at $\$800 \times 10^9$ (Kuzenovic et al. 2008), whereas according to estimations of the Public Power Corporation of Greece (PPC), 35% of the cost of electricity production facilities comes from the cost of networks. Additionally, building and maintaining this infrastructure requires well-trained personnel and significant time and machinery. Problems occurring in these networks lead to outages, sometimes felt as interruptions to the customers.

The impact of a major power outage will be determined by the nature of the affected area, the duration of the disturbance, the time of day, the weather conditions, etc. A major blackout will affect all functions in a society, and economical activity stops in a region without electricity (US–Canada Task Force 2004). People in large cities will usually be more affected than those living in rural areas. Indirect effects of a blackout can have a major spread in time and space, for example, an increase in crimes in larger cities, interruptions in communications and transportations, and low indoor temperatures during wintertime. Especially critical is the state of dependence between telecommunications and power systems. After a few days there can be a shortage of food and fuel, which affects the reserve supply of electricity from backup generators.

Therefore, it is necessary to understand to what extent the energy networks are vulnerable to climate, how much their operations are affected, and how we can decrease vulnerability based on the experience of utilities around the world. The structure of this section is as follows.

First, a small summary of how electricity networks and fuel pipelines are structured is provided for the reader unfamiliar with these infrastructures. Then, how extreme weather effects and changes in the sea level affect the T&D networks will be analyzed. At the end of that section a summary table of the level of vulnerability and the associated costs will be provided for each one of these weather effects. The next section refers to how the T&D networks could potentially help in mitigating climate effects, and emphasis is given on the recent advances reducing losses on these networks and the potential impact of Distributed Generation (DG). Finally, suggestions for the operators and developers of T&D networks and fuel pipelines are made.

3.10.2 Introduction to Electricity Networks and Fuel Pipelines Infrastructure

In this section, a short introduction to the structure of electrical networks is made. The necessary clarification between transmission and distribution networks is made and some general outlines of their construction and operation is given. This is essential so that the reader can have an adequate grasp of the notion of electrical grids and understand their potential vulnerabilities to external impacts. Also some details on fuel pipelines will be provided.

3.10.2.1 Construction Details

3.10.2.1.1 Transmission Systems

Transmission systems consist, in the vast majority (estimated at 95%) of the lines built, of overhead lines using tall steel towers with different configurations, depending on the voltage level, the transmission capacity, and any special precautions due to, for example, crossing a river or passing through a mountainous area. There may be a single circuit or double circuits at one tower, depending on its design.

The higher the transmission line voltage, the higher the steel tower and the wider the area required. For instance, a typical single 150 kV transmission tower has a width of 13.6 m, whereas a single circuit 400-kV overhead line has a width of 20.6 m. The distance between successive towers ranges between 150 and 500 m depending on the ground morphology and any potential obstacles, whereas distances larger than 1 km have been recorded (see bibliography). Typical transmission lines are shown in Figure 1.

The vast majority of transmission lines operate at AC, but transmission at DC level has started becoming popular for long distances and interconnections with submarine cables like the interconnection of British and Dutch transmission networks, NationalGrid, and TenneT (BritNed Go Live video 2012).

3.10.2.1.2 Distribution Networks

Distribution lines are further divided into medium voltage (MV) and low voltage (LV) levels. Distribution networks are extremely extended, with thousands of kilometers around the world to reach the final customers. In Europe, the European Network of Transmission System Operators (ENTSO-E) controls 200 000 km of HV lines (ENTSO-E 2012), which is the same as the length of distribution lines solely in Greece. The overhead lines of this type usually consist of wooden or sometimes concrete poles. Figure 2 shows a typical transformer of MV/LV, 20 kV/400 V in a crossroad in the suburbs of Iraklion, Crete. On top of the poles are the MV lines, and the 5 lines below are the LV lines (three phases, one neutral and one phase also feeding the street lighting).

3.10.2.1.3 Network Topologies

Transmission networks, due to their significance for meeting demand, are usually constructed in loop or meshed architecture. In this way if one line for some reason is unavailable, either due to failure or due to maintenance, the flow to the rest of the network will remain. This is the N-1 criterion. In some cases, an N-2 or even N-3 criterion applies. Radial transmission lines are usually used for meeting the demand of relatively few and remote customers.

Distribution systems sometimes are meshed as the transmission systems, mainly for MV main feeders. For most low voltage networks, especially in rural areas, they are radial. This means that if a part breaks down, the related customers remain without electricity.

Both radial and meshed networks are shown in Figure 3.

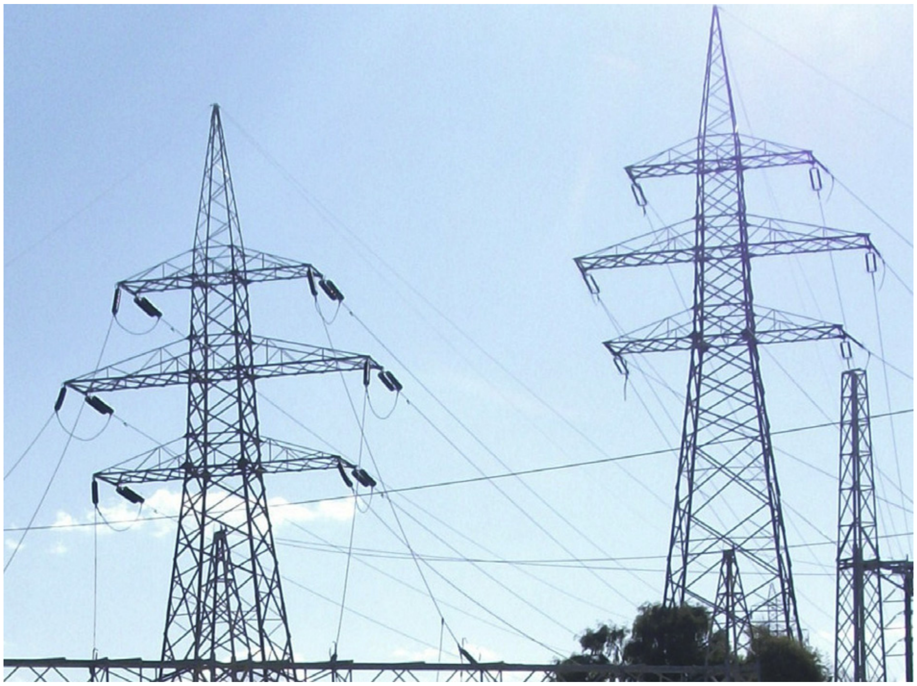

Figure 1 Typical high voltage towers (150 kV).

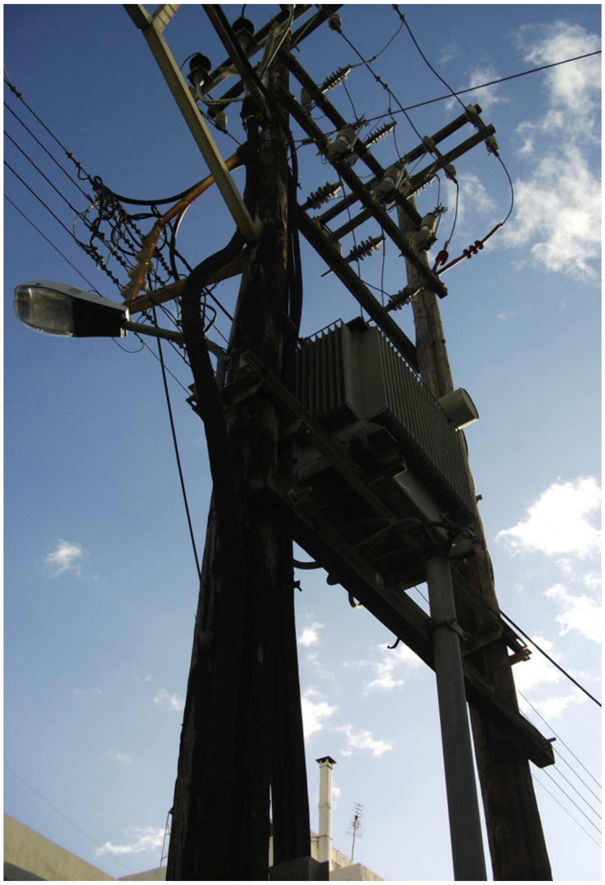

Figure 2 Typical MV/LV transformer and distribution level construction.

Table 1 describes the typical voltage ratings for electricity grids used by utilities around the world. Ratings above 230 kV are considered as extra high voltage. More details and maps of transmission systems can be found at the web sites of transmission system operators (TSOs) and the ENTSO-E.

3.10.2.2 Causes of Outages in Electrical Grids

An attempt is made here to distinguish the concepts of outages and interruptions in order to facilitate the reader's comprehension of the causes of outages in electrical grids. Outage is the breakdown or scheduled maintenance of a network component, meaning that this component is temporarily out of service. 'Interruption' means cessation of service to customers. Outages may cause interruptions but this not always the case. Very often outages take place but are not noticed by the customers at all. Additionally, the duration of an outage is usually longer than the interruption time because, using different network routes or even backup generators, some or all customers served by the faulty equipment can be served after some time.

Weather is one of the most important causes for outages. In normal weather, grid faults are occasional; under adverse weather, outages occur more often. The lower the voltage, the more frequent such events may be, but much fewer customers are affected.

Under extreme weather conditions, however, the outages occur increasingly often and may be caused by severe damage to the equipment itself. For instance, based on the Hellenic Transmission System Operator (HTSO) reports for 2011 (HTSO-Web-site 2012), at least 1100 MWh were not served due to adverse weather conditions and outage at the

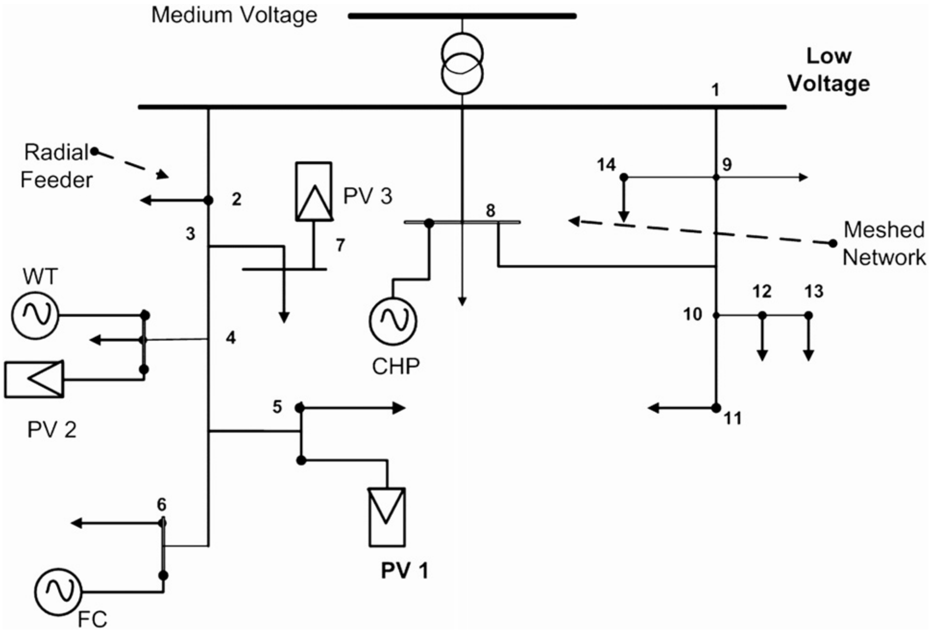

Figure 3 Typical distribution network with radial and meshed feeders and DG sources connected.

Table 1 Indicative line-to-line voltage level for distribution and transmission grids

Transmission level	*Medium voltage distribution level*	*Low voltage distribution level*
66 kV, 132 kV, 150 kV	6.6 kV, 11 kV, 15 kV	110 V, 220 V, 400 V
220 kV, 380 kV (Swiss)-400 kV, 500 kV, 750 kV (extra high voltage)	20 kV, 21 kV, 33 kV	Generally below 1 kV

transmission level. These reports do not mention related faults at the distribution level.

With respect to extreme weather events, snowstorms are regarded as events with both the highest duration and amount of energy not served, whereas lightning and extreme wind conditions are also frequent causes of outages and interruptions. Other events related to climate variability such as sea level rise, increased precipitation, drought, and rise of temperature could also affect the operation of electricity networks either in the short or longer term. Considerations of climate impacts would even require a reconfiguration of the existing electricity grid, namely the inclusion of adaptation measures in the planning procedure.

3.10.2.3 Oil and Natural Gas Pipelines

Because of technical and security reasons, pipelines are usually underground with checkpoints at the ground level. At various points along the pipeline, including at line junctions, compressor stations pressurize the natural gas to ensure a continuous and regulated flow. Transport lines vary in size, generally ranging from 24 to 36 inches in diameter, and have right-of-way widths of up to 200 feet, depending on the size and number of lines. One final point near seaside may be a terminal station either for compressing or storing liquified natural gas (LNG).

Oil pipelines may either end at a terminal station or at a refinery. The pipelines are very often constructed with polyethylene HDPE or with metals. Being underground, they are not as exposed to extreme weather conditions as electricity networks are, except in cases of coastal location affected by sea level rise. The main fault that may take place is their destruction, break at one point, or corrosion. The main issues that may exist are the ones of increased consumption and destruction of the soil. Where available, some information will be provided in addition to that given for electricity networks.

3.10.3 Vulnerability to Climate Variability Phenomena

3.10.3.1 Cold/Ice Storms

Transmission lines have been designed to account for increased levels of snow cover on them. Similar but not so strict precautions have been taken for distribution networks as well. Unusual snow cover, however, especially in high-temperature areas where the tension of the line gets lower, may create falls of conductors more often due to the weight of snow or ice. This may get even worse when the temperature drops to around 0 °C together with high precipitation and wind, which very often leads to wet snow accumulation reaching even 20 cm on overhead power lines. Experience from such events with impressive but discouraging examples can be found in cold climate countries like Iceland (Elíasson 2005). Experts on transmission systems consider this phenomenon to be the main icing problem.

Combination of wind and ice cover is the most threatening scenario for overhead lines. The surface of the line exposed to wind is wider as the snow becomes ice. Therefore, in addition to ice weight, mechanical stress caused by wind increases because of the cross section of the line, as can be seen in the simplified diagram in Figure 4. This precaution has to be taken into account when calculating the mechanical characteristics of the line and the span between successive towers.

Wind combined with snow can create even more problems by carrying precipitation with high salinity, sand particles, or other pollutant material to the insulators. Under these circumstances, insulators may suffer from flashover.

Climate variability impacts include extreme snow cover and frequent events of extremely low temperatures even in areas not so familiar with such weather phenomena, thereby causing severe consequences due to less experienced personnel.

To make matters worse, under such weather conditions access to the faulty equipment becomes particularly difficult, hence prolonging the interruption. The longest duration of outage caused by weather in Greece in 2011 was 9.5 days due to fallen transmission towers in the windy area of South Evia near Athens during increased snowfall. This area is shown in Figure 5.

In January 1998, Eastern Canada was hit by the worst ice storm in modern time. 1.6 million users were left without electricity and a large share of the 5.5 million inhabitants of the region suffered from power outages. In some areas, the restorations took nearly 4 weeks, and residual repairs of the power grid continued into early summer (Fischer and Molin 2001). A similar event in Germany in 2005 led to collapse of 70 transmission towers, leaving 200 000 people without electricity (Fikke et al. 2007).

3.10.3.2 Lightning

Lightning is a severe event mostly for transmission and distribution equipment. According to a recent Metoffice presentation (McColl et al. 2011), lightning is the primary cause of outages in transmission lines and the second most frequent cause for distribution lines. Lightning is found to cause damages to distribution lines in urban areas very rarely, contrary to rural areas.

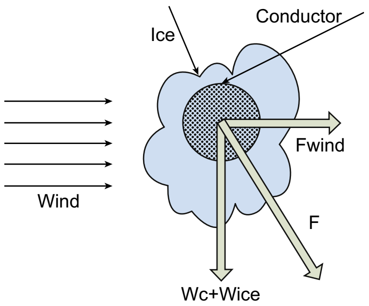

Figure 4 Simplified diagram of forces on a conductor with ice under windy conditions.

One important example of a blackout attributed to lightning took place in Brazil on March 1999 when 97 million customers were affected by a cascading transmission fault initially caused by lightning strike, which cut electricity for about 5 h. Another characteristic event of repeated lightning strikes is the one recorded in 18 January 2010 on the island of Crete (Thalassinakis and Papazoglou 2010). During this incident, nine lightning strikes were detected within a few kilometers of the largest city of the island, Iraklion, near the power station and the dispatching center. Within 19 min and under heavy rainfall, a brownout of the power system of the island was created. This was mainly due to protection coordination, the experience of personnel at the dispatching center, and the high spinning reserve that helped in avoiding a total blackout of the autonomous power system of Crete. Even though the electricity cut lasted for few hours, critical equipments, such as generators, were efficiently protected and allowed the power system to recover quickly from this disturbance. A list of other blackouts triggered by thunderstorms can be found in Chapter 6 of Knight (2001).

Overall, the electrical equipment manufacturers, in cooperation with utilities, have developed protection schemes in order to mitigate effects of lightning to equipment and human life. Also they have made significant progress in equipment used to protect final customers from breakdowns in their equipment due to lightning strokes.

Regarding pipelines, direct strike of lightning is not as intimidating as for electricity lines because pipelines are not the highest objects in their area. What may be threatening is the side effect of lightning on electricity network infrastructure due to voltage rise on the ground proximate to the lightning strike. In such a condition, breakdown of polyethylene may occur, depending on the circumstances. The result of this incident may be a hole in the pipeline resulting in gas leakage, the severity of which depends on the current discharge of the lightning strike, and the dielectric constant of both the pipeline material and the special resistance the soil presents (Caulker et al. 2008).

Thunderstorms are likely to be more intense and/or frequent (IPCC 2007); thus efforts for protecting equipment against this event should be intensified during the adaptation process. Furthermore, efficient coordination of protection devices and sufficiently trained personnel is required to alleviate the impacts after a lightning stroke. If these considerations are not taken into account, some transmission or distribution equipment may be destroyed and electricity cuts may last longer.

3.10.3.3 Wind

Climate effects include frequent extreme wind speeds, and a possible increase in the probability of local hurricanes. Wind is a severe threat for both transmission and distribution network overhead lines by affecting their operation in one of the following ways:

- Dismantling of one or more of the conductors due to their vibration.

This may happen if wind has the power to take away one of the conductors of an overhead line. Usually, precautions, such as dampers loops (bretelle), have been taken in order to mitigate this effect.

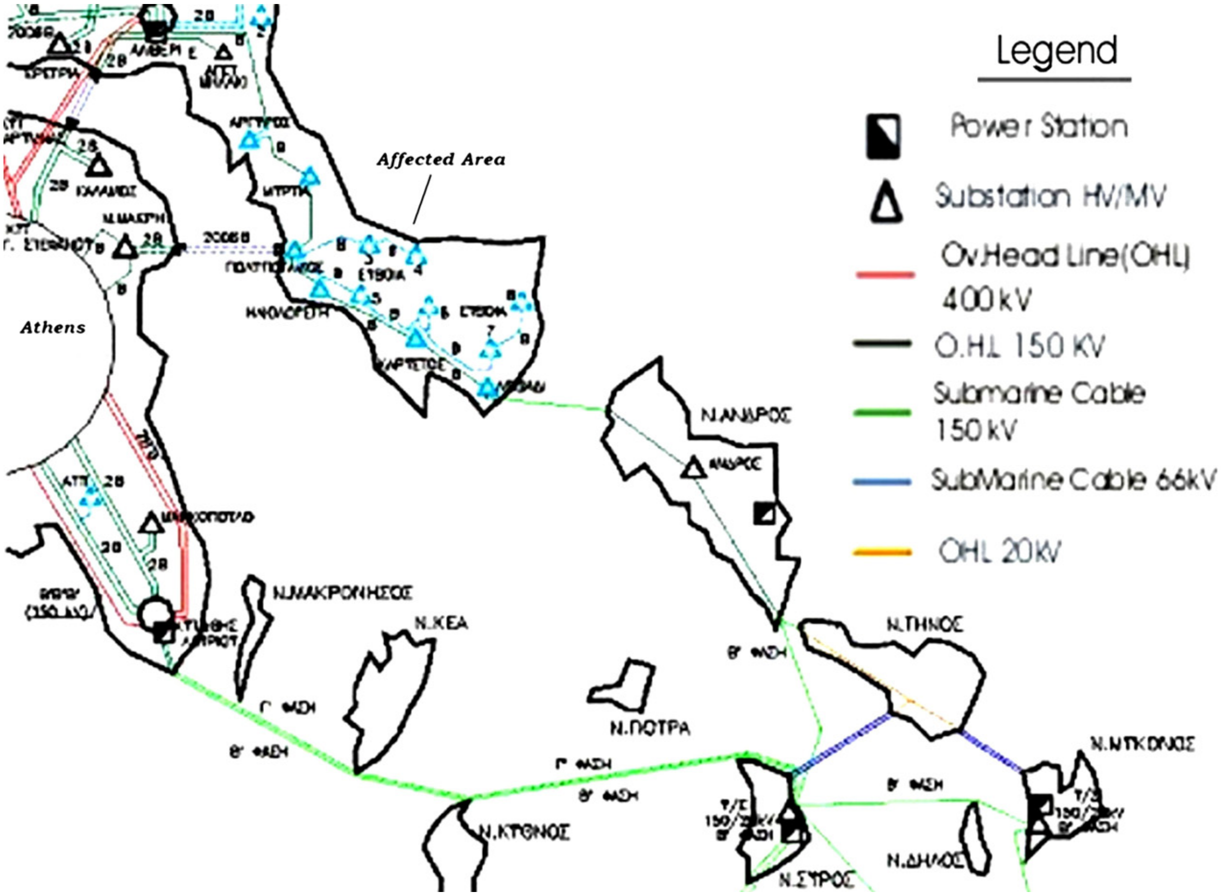

Figure 5 Map of the affected area. This map shows the scheduled interconnections of the Cyclades islands to the mainland (Hatziargyriou Vrontisi et al. 2007).

- Trees falling on transmission and distribution lines.

This is a frequent event especially with regard to distribution lines running across forests or suburban areas. It is estimated that 50% of the faults taking place at the distribution system level are caused by falling trees. During ‘Lothar’ and ‘Martin’ storms in France in December 1999 (Ward 2010), 90% of the faults in the distribution networks were caused by falling trees causing disconnection of 415 million kWh mainly due to distribution system disturbance.

- Under high wind speed circumstances parts of trees may fall on distribution lines.

The simplest disturbance caused by this event may be that a line grounds to short circuit. Usually, this is cleared by the protection devices of the distribution networks, leaving customers without electricity. However, by taking away the tree or branch the disturbance is resolved. A more severe impact of high wind speeds may be a three-phase fault when a branch or a tree remains on the three conductors of the overhead line. Even at these milder situations, a collapse of trees on distribution lines causing the poles to collapse is likely but with relatively limited consequences. Such an event will require more personnel hours in order to fix the damage than simple electrical faults. The duration of electricity cuts will increase significantly as similar events occur more often.

- Objects on the lines.

Increased wind speed may cause some objects to ‘fly’ over some distances and finally land on the transmission lines. This happens at least once per year at the transmission system of Crete, with nylons used in greenhouses found landed on a section of a transmission line. Increased frequency of high wind speeds will result in an increased frequency of such incidents.

Wind combined with low temperatures and rain may create wet snow effect, thoroughly described in the cold/ice subsection.

3.10.3.4 Rise of Temperature and Electricity Networks

Generally, the capability of electricity networks to transfer electricity is decreased when the temperature increases. At the same time Ohmic losses are increased as can be seen in the following formula:

$$R_2 = R_1 \frac{T + t_2}{T + t_1}$$

where R_2 and R_1 are the conductor resistances at t_2 and t_1 °C (Saadat 2004).

The overload capacity, the efficiency, and the lifetime of the transformers are reduced under high temperatures. Extreme temperatures adversely affect the insulating properties of the transformer. Problems have occurred with transformers designed to cool off at night being unable to cool down sufficiently during warm nights and therefore begin the next day with higher starting temperatures. This is the major cause of most transformer failures (Georgilakis 2009). An additional issue raised by the British Columbia Hydro is the association of temperature increase with beetle infestation (Cigre Tutorial 2011). BC Hydro express their concern as regards the correlation of vegetation and network infrastructure by providing a specialized section on their website dealing with this issue (BC Hydro 2012).

With regard to underground cables, the expected increase in soil temperature may not be as high as in air temperature; however, temperature drain is an essential parameter for the loading of the line. Therefore, the capacity of the electricity grid to transfer power to the customers is reduced as the temperature rises and hence the capacity of the same transmission or distribution line will be lower than under normal conditions.

Heatwaves are expected to become more frequent (IPCC 2007) and as a result the extreme temperatures during summer periods will decrease the capacity of electricity networks. This will pose difficulties in meeting the summer peak demand that is found in most southern European countries, as in the case of southern Greece in July 2004 (Vournas et al. 2005). As a consequence, during heatwave periods the interruptions due to a decrease in both generation and network capacity are expected to become more frequent, unless costly investments in electricity infrastructure take place along with energy efficiency measures on the demand side of power systems.

3.10.3.5 Drought

Droughts do not pose a direct risk for operation of electricity networks as do other climate disturbances examined above. However, specific cases when droughts create complications to the functionality of electricity networks have been detected. The most severe impact of droughts is the increased risk of fire and thus the possible destruction of wooden poles or transmission lines. If such an event takes place, both the restoration time and the resources (capital and human) required for restoration are significant.

Another issue to be considered in cases of drought combined with moisture and salinity is insulator flashover. Salinity and dust due to drought remain on the insulators and when combined with moisture, favorable conditions for insulator flashover can be formed that may lead to their destruction and the consequent faults on the transmission lines. Utilities using helicopters for transmission networks or water carrier trucks wash the insulators at both the transmission and distribution networks during the summer time. To combat this problem, new silicon-coated insulating materials have been developed (Siderakis et al. 2008).

Drought can limit the moisture on the ground, increasing local temperature and thus reducing the capacity of underground cables. Decrease in moisture of the soil decreases electrical conductivity of the soil, increasing the grounding resistance of the substation or other equipment grounding system. This may affect the ability of the faulty part of the transmission or distribution network to 'clear' the fault (caused, e.g., by lightning or short-circuit).

Generation facilities, in particular hydroelectric and thermal ones, are far more vulnerable than electricity grids to drought as has been examined in previous sections. Thus, a change in electricity flow can be seen, resulting in increased loading or even overloading of specific lines. Thus, this vulnerability of power generation combined with non–weather-related events in the transmission systems could create blackouts that otherwise could have been avoided. More details on this issue can be found in the generation facilities-related chapter and in reports for Western Utilities (DOE 2009) and especially Texas (Webber 2012). Drought concern in Texas is rather high as the Electric Reliability Council of Texas (ERCOT) has recently organized a drought best practices workshop (ERCOT 2012).

3.10.3.6 Floods

Floods do not constitute any significant threats to electricity networks owing to the height of the transmission and distribution lines. However, distribution networks with lower height from the ground are more exposed to such a threat. The most severe threat for overhead lines comes from the wet soil of foundation factor that, especially under windy circumstances, might lead to collapse of some wooden poles.

High voltage/medium voltage substations are more vulnerable to floods because they are mostly installed outdoors. Part of the installation may get flooded much easier than an overhead line. In such a case, the substation goes out of order, leaving hundreds of customers without electricity. The repair of the installation would require the drainage of the water away from the facility and possibly the substitution of significant part of the equipment, which are capital- and human resources-intensive procedures. Low lying areas are more vulnerable to this event. One significant outage was recorded in the Philippines in 2009 during the typhoon Ondoy, which flooded three 230-kV substations including the one feeding the Luzon Metro system (NGCP 2011).

Less severe due to fewer customers affected, but more probable, is the flooding of MV/LV underground or ground floor substations that can be found especially in urban areas. Building such substations is not an uncommon practice in most cities of the world due to lack of space and esthetic reasons. Generally, utilities have taken precautions during the construction of substations in order to ensure water drainage, but improved drainage and antiflood measures of new substations are regarded as possible adaptation measures.

Overall, future energy projects located in flood prone areas will face increased capital costs due to both legislative and insurance pressures.

3.10.3.7 Rise of Sea Level

An important consideration for adapting to sea-level rise is the location of energy infrastructure, namely power plants, substations, and networks. Especially because this impact would only appear at a significant magnitude in the long term, it is expected that utilities and network operators will plan new investments accordingly.

The water level rise is not expected to create more severe problems than the floods; thus vulnerability of transmission and distribution lines can be considered almost negligible. During the forthcoming years, however, significant numbers of undersea cables are going to be laid to interconnect insular areas or large power systems in Europe and North Africa (Desertec 2012). Therefore, this should be taken into account before laying these cables. The precautions that should be taken mainly involve the relocation of infrastructure at a higher altitude. Additionally, natural gas infrastructure and in particular LNG terminals – commonly located on coasts – may also require relocation; pipelines near the shore may have to be transferred to higher elevations as well as terminal stations for tankers.

3.10.3.8 Landslide

Landslides are expected to occur more frequently as a result of increased rainfall or rapidly melting snow. Such an incident may threaten distribution networks that are erected on wooden poles and are generally weaker than steel constructions of transmission lines and hence much easier to collapse. These events may not occur as frequently as disturbances due to ice, wind, or lightning, but the restoration time once a part of the electricity network is damaged is much longer. Such an example comes from Taiwan in 1999 when one transmission tower collapsed, leading to 8.5 million customers disconnected (Lee and Hsieh 2001).

Landslides can also affect natural gas pipelines, like the rockslide transformed into a debris flow severing a natural gas pipeline in Western British Columbia in June 2002 (Boultbee et al. 2006). Another important issue related to increase of average temperature is the melting of permafrost in Arctic regions and the consequent impacts on infrastructure and especially fossil fuel pipelines that may result from the melting. Russian scientists have expressed their related fears during a workshop in Iceland (Cigre Tutorial 2011).

3.10.3.9 Discussion of Vulnerability of Networks to Climate Variability

Overall, from the analysis above regarding the vulnerability of energy networks to weather effects, it can be concluded that extreme climate variability may lead to the malfunction of electricity and other energy networks. In terms of frequency and intensity of impacts, ice storms are considered to pose the greatest risk to electricity networks, especially when combined with wind, whereas other impacts such as floods, landslides, and sea level rise are considered milder.

Compared to electricity networks, pipelines, usually being underground, are more vulnerable to any parameter affecting the ground like floods and landslides and are rather vulnerable to sea level increase when LNG tanks are considered. Table 2 summarizes the frequency, restoration time, and cost of restoration for the above-mentioned effects, using descriptive variables as stated in Table 3.

Ranking the weather effects, taking into account their frequency to occur as described in Table 2, the restoration time, the number of affected customers, and the restoration cost, we can derive a vulnerability matrix as described in Table 4. This comes from assigning values 1 for low frequency or small impact and 3 for high frequency or high impact and multiplying these three values. The maximum vulnerability is 27 points. Clearly, electricity networks are more vulnerable to cold\ice storms and wind.

3.10.4 The Role of Electricity Networks in Mitigating Human Impact on Climate Variability

Planning of electricity networks is considered as an important measure to react to climate effects. The most important contribution to climate mitigation is the increase in the efficiency of transmission and distribution to final customers, leading to decrease in energy losses and thus enhancement of

Table 2 Weather events and their impact on networks

Weather event	*Frequency of problems caused*	*Restoration time*	*Cost of restoration*
Cold/ice storms	Medium–high	Medium–high	Medium-high
Lightning	High	Small–medium	Small-medium
Wind	High	Small–medium	Medium
Floods	Low	High	Medium to high
Temperature rise	Medium	Medium	Small to medium
Drought	Low–medium	Short–medium term	Medium
Rise of sea level	Very low–low	High	High
Landslides	Low	High	Medium

Table 3 Explaining ‘fuzzy’ variables

Characterization	*Frequency of problems caused*	*Restoration time*	*Cost of restoration*
Low	Rather rare events	Less than one day	Limited equipment needs replacement
Medium	May happen once per year	Less than a week	Replacement of some equipment, e.g., few poles a couple of tower
High	Quite possible when such conditions have been predicted	More than a week	Significant capital required

Table 4 Vulnerability

Weather event	*Electricity networks vulnerability index*
Cold/Ice storrns	15
Lightning	7
Wind	11
Floods	7
Temperature rise	6
Drought	5
Rise of sea level	4
Landslides	6

energy savings. This can be achieved either by utilizing more efficient equipment or by more efficient management of the existing equipment. The latter can be a way of improving access to 'cleaner' energy resources existing in remote or even harsh weather areas. This paragraph will provide some main measures that aim at the improvement of network efficiency.

3.10.4.1 Improvement of Equipment Aiming at Loss Reduction

3.10.4.1.1 Advances in Transmission Lines

One significant advance in cabling technologies is the development of high-temperature low-sag (HTLS) transmission lines. This technology reduces the sag of the cable, making contact with trees less likely to occur. Additionally, the technology presents lower resistance than the existing overhead lines and higher current rating, both of which result in fewer losses. Moreover, they can replace conventional conductors with no (or minimal) modifications to structures. The most important benefit of this technology is that it can significantly increase the rating of a transmission line with no (or minimal) licensing requirements or public opposition and in a very short period of time.

Examples of major installations in North America that use cables with this type of technology can be found in Clairmont (2008). In the same document, the measurements taken and some installation photos are also provided. Regarding Europe, a comparative study on these technologies from Ireland (Kavanagh and Armstrong 2010) indicated the Gap technology as most suitable. Compared with the current installation of ACSR cable with 943 A for 430 mm^2, the Gap conductor has a thermal limit of 1409 A. On the island of Crete, the ACSS conductor type is used to replace ASCR lines using the same towers in the Ierapetra–Sitia 150-kV transmission line.

3.10.4.1.2 Improved Transformers

Transformers help in changing voltage amplitude from generation level to transmission/distribution level and finally to the final customer. A simple system of the required transformers of a relatively small power system necessary to transfer electricity from production point to consumption is shown in Figure 6. The voltage ratings are typical values of networks in Greece. One can easily see that there are at least three transformers on our way to the customer. Each one of these transformers presents a variety of losses (Olivares-Galvan et al. 2009). Most important are iron losses constant with the load and copper or load losses changing with the loading of the transformer. When the load is doubled, these losses are increased four times. One typical 400-kVA transformer, enough to provide power to a village of 400 people, has around 6 kW of ohmic losses at full load. Improvement of the efficiency of the transformers increases overall efficiency of the power system and thus helps mitigate greenhouse gas emissions.

Significant effort has been made in improving the efficiency of transformers. Some of these efforts have targeted minimizing no load losses through improved design of the transformer by using more conductive materials and trying to reduce copper losses (Georgilakis 2009).

3.10.4.2 Loss Reduction by Reactive Power Compensation

Ohmic losses are proportional to the square of the electric current; therefore, by reducing the electric current one can reduces losses, while the useful power transferred is unaffected if higher voltage levels are applied. Thus an increase of voltage level can mitigate network losses.

Losses are higher at peak demand due to increased values of current. For example, on the island of Crete in 2001, the losses were 2% at low load and 3.3% at peak load (Thalassinakis and Gigantidou 2012, personal communication).

What should be taken into consideration is that electric current has two factors, one of active power P (i.e., the power that produces useful work) and the other of reactive power Q, which is necessary to create the electromagnetic field in electric machines but which does not produce any useful work. This is clearly shown in Figure 7, where complex power S is the vector of summation of P and Q. Increased reactive power increases the electric current and hence increases network losses.

Reactive power compensation is a common practice among utilities in order to reduce network losses and increase voltage stability of the network. Means of reducing the reactive power include the use of shunt capacitors with simple or more sophisticated – power electronics driven – switches.

3.10.4.3 Network Reinforcement for Access to Areas with Increased Renewable Energy Sources (RES) Potential and Weak Networks

Increased RES penetration results in greenhouse gases reduction. Quite often areas with rich RES potential are sparsely inhabited. Such areas may be windy areas, islands, or even deserts. In order to exploit this high RES potential, significant network infrastructure is required. The vast majority of network reinforcements refer to improved access to areas with high RES potential. Such are the plans for Euro-Mediterranean interconnections primarily aiming at the utilization of the excessive solar potential of the deserts. Building concentrated solar power (CSP) plants in the Sahara desert requires significant transmission system capacity and undersea DC cables (Desertec 2012). In China, there are areas with very favorable wind conditions but due to the distance from the centers of consumption, its exploitation requires significant efforts on building transmission lines (Jiang et al. 2011). Similar issues are faced in the United States, where many of

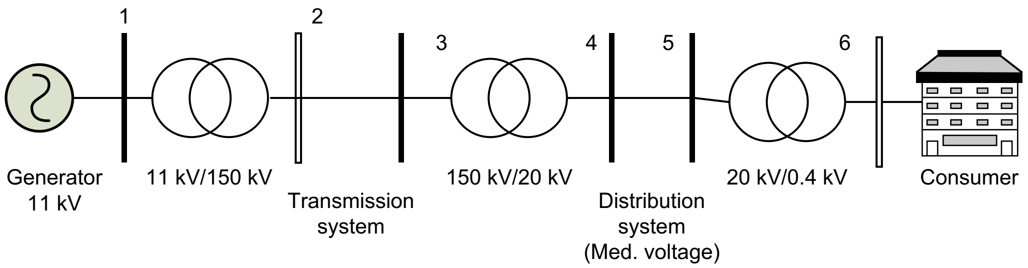

Figure 6 Typical structure of the network for meeting the demand of a consumer, focusing on transformers.

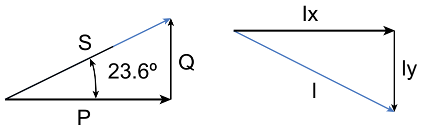

Figure 7 The triangle of active P and reactive power Q and the corresponding currents Ix and Iy.

the best wind resources are away from existing transmission corridors, and also facing the issue of who is going to pay for this reinforcement (Piwko et al. 2011).

The interconnection of Cycladic islands with the mainland of Greece (Hatziargyriou et al. 2007) is a relevant project ready to start construction while interest in interconnecting most of Greek islands with the mainland has recently been expressed by policymakers (Papadopoulos et al. 2007). The core idea behind the proposals for new interconnection projects is the exploitation of favorable wind power conditions of eastern Greece and the Greek islands.

Efficient management of existing network infrastructure could enable the simultaneous building of generation facilities and transmission networks. Suitable control schemes can be applied to alleviate network congestion due to increased RES penetration. In that way, most of the RES production can be fed to the grid even prior to the finalization of the transmission system expansion. The HTSO that manages wind parks in the northeast region of Thrace in Greece followed a similar methodology in order to avoid rejecting produced wind energy before the finalization of transmission system upgrades that are constructed for the UCTE-Turkey synchronous interconnection. In particular, the methodology followed was the introduction of 'interruptible contracts' and the continuous monitoring and control of the power flow through the congested corridors by issuing a set-point to each wind farm (WF) of the area to reduce its production, whenever system security was endangered. The control concept was applied according to the following rule: "The power flow through the interconnecting lines is not allowed to exceed a predefined security limit." This limit was calculated with respect to the N-1 security criterion according to the Grid Code regulations. In case of limit violation, the controller would send set-points to the WFs with interruptible contracts to reduce their production, if necessary.

The necessary power reduction was to be shared by all WFs with interruptible contracts. The control scheme was implemented using an autonomous system comprised of programmable logic controllers (PLCs) communicating to each other through two different and independent telecommunication lines. The existing SCADA system was utilized for monitoring and settlements if necessary. More technical information on this issue can be found in Kabouris and Vorunas (2004) and Kabouris and Michos (2005).

3.10.4.4 Distributed Generation

According to the European Commission, "Current grids have served well but will not be adequate in the future: grids must ensure secure and sustainable electricity supplies throughout Europe, take advantage of new technologies and comply with new policy imperatives and changing business framework" (SmartGrids 2006). A new era of grid planning has arrived that will integrate in an optimum way microproducers and microconsumers of power. DG will be a significant feature of the new energy system, well combined with the centralized system already in place.

Even though there is more than one definition of distributed generation, it is agreed that the following terms refer to the same idea: distributed, dispersed, decentralized, or embedded generation (Jenkins et al. 2000). Distributed generation is production sharing the following characteristics:

1. It is not centrally developed (from utility or administrator).
2. The power system operator does not schedule its production.
3. The installed capacity is below 50–100 MW.
4. It is connected to the distribution system either at medium voltage or at low voltage.

The driving forces for installing distributed generation include, among others, the increase in reliability, the use of local fuels (e.g., biogas), combined heat and power production to improve overall efficiency (Pecas Lopes et al. 2007), or the variability of renewable energy sources. The attractive financial environment (e.g., high remuneration prices for integrating PVs on buildings) is also one parameter leading to development of production installations near consumption. The units, either RES or conventional, usually used for this purpose can be classified from Figure 8.

Advances in each of these technologies can be found in various textbooks, either for the distributed generation (Jenkins et al. 2000; Willis et al. 2000) or in specific textbooks for each technology (Larmine and Dicks 2000; Soares 2007). Additionally, review articles on the advances in each technology have been published by various editors (Hansen and Hansen 2007; Kaisare and Vlachos 2012; Peppermans et al. 2005).

3.10.4.4.1 Microgrids

It is now well understood (Hatziargyriou et al. 2007), that DG cannot operate under the 'fit and forget' principle anymore, but some level of DG aggregation and control is required. Aggregation expands the DG benefits and can provide additional support to the operation of the electricity networks.

One of the potential methods of aggregation is the formulation of microgrids, which are low or medium voltage grids with distributed operation. Microgrids usually have storage devices such as flywheels, energy capacitors or batteries, and controllable loads such as water heaters or air conditioners that can be connected to the main power network or be operated autonomously in a coordinated, controlled way. Microgrids mostly not only operate interconnected to the main distribution grid, but also islanded in case of external faults.

In terms of power grids, a microgrid can be regarded as a controlled entity within the power system that can be operated as a single aggregated load. Given attractive remuneration it can be regarded as a small generator or even as an ancillary service to support the network. In terms of AC customers' energy services, microgrids deliver thermal and electricity needs to the customers, enhance local reliability of supply, and improve power quality by supporting voltage and reducing voltage dips. They are also considered a means of reducing emissions due to the reduction of network losses and potentially as a means of lowering costs of energy supply.

It is clear that in order to achieve these benefits, it is important to provide a coordinated decision making process, one that facilitates a balance between demand and supply from both distributed and centralized sources from MV distribution feeders. Description of this hierarchy in combination with the following two potential market policies for microgrids operation is provided by Tsikalakis and Hatziargyriou (2008). These two market policies foresee that microgrids maintain zero reactive power serving their own customers' needs and thus minimize cost; at the same time, microgrids buy and sell power to the grid aiming for profit maximization.

Such operation requires exchange of information between a central controller and the local controllers that may represent either a generation unit or a controllable load, regarding market prices of each controller. The implementation of such a scheme also can be made using software agents (McArthur et al. 2007).

Operation of microgrids can be further developed and control options can be designed in order to achieve some additional benefits like demand side bidding (participation of the loads in the market), participation in emissions markets (Tsikalakis and Hatziargyriou 2007), cooperation for voltage regulation within the microgrid (Geibel and Reimann 2011), coordination for black start capabilities (Pecas Lopes et al. 2005), and coordination for providing ancillary services to the upstream network (Joos et al. 2000).

Additionally, this coordinated operation and the fact that the capacity is increased in the proximity of the consumption can help significantly in the deferral of investments in electricity networks, especially at the distribution level (Gil and Joos 2006).

Microgrids can increase the already significant benefits in terms of economic operation, losses reduction, and emissions avoidance of distributed generation (Hatziargyriou et al. 2011; Costa and Matos 2009). Reduction in losses helps in further reduction of emissions.

Significant research on microgrids is being conducted all over the world in order to propose the most promising market

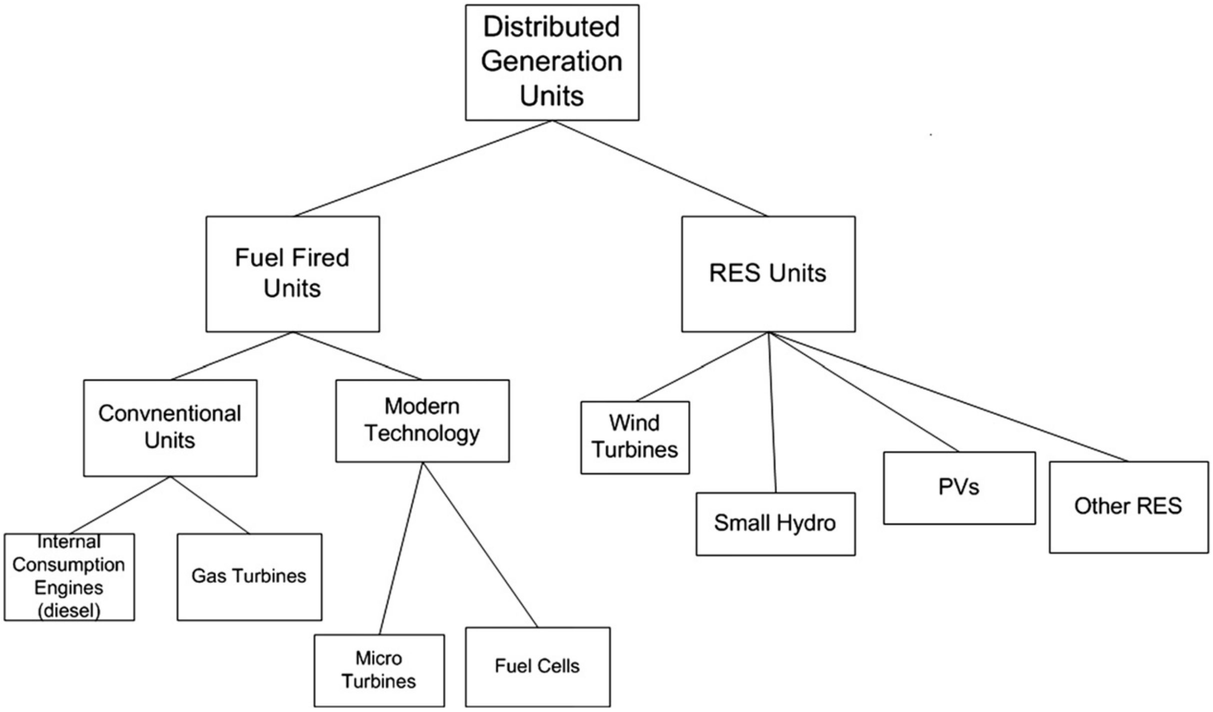

Figure 8 Classification of distributed generation.

operation schemes, to alleviate any potential technical problems like islanding operation with inverter-dominated networks, and to tackle regulatory issues (Kroposki et al. 2008; Satoshi 2007). Algorithms and hardware have been developed in order to implement new facilities from microgrids and some of them have been successfully tested in various test sites.

A more market-oriented control approach that does not require direct connection among the DG units, as do microgrids, is the one of virtual power plants (VPP) (Asmus 2010). Under the VPP operational framework, different DG units, which can be rather far away to be considered as a network neighborhood, can cooperate in order to operate as one market entity as if these units were one plant. This is why this approach is called *virtual power plant*.

Therefore, distributed generation and its coordinated operation either in microgrids or in VPP can provide substantial help in facing the problems of electricity networks related to human impact on climate variability or even help in mitigating the emissions related to electricity production.

3.10.5 Suggestions

In order to reduce vulnerability of networks to weather extremes, careful planning and locating of infrastructure should be made by incorporating all available information as regards the geography of climatic variability. Decision makers should also take into consideration that network infrastructures have a very long lifetime, thereby long-term climatic variations and especially sea level rise must be accounted for. Planners should also integrate criteria related to extreme weather effects, and countermeasures should be considered as part of the normal development of the network.

One tool of significant importance for this purpose is the use of geographical information systems (GIS) (Meehan 2011). This is of great help when building geographic models and calculating the exposure of segments to extreme whether conditions. Without the use of the current GIS software, these tasks would have been extremely burdensome or even impossible. More generally, GIS could improve and facilitate the planning and operation of transmission and distribution networks. Mapping via GIS can help in identifying outages even more quickly and thus more quickly restore any faulty equipment.

The physical capital of the energy system must be upgraded or planned according to adaptation measures described above. Specific measures can be taken to combat the effects of different climatic characteristics, like antiflood measures to avoid floods and landslides that can be integrated in the general upgrade of the equipment.

Appropriate human capital development is also required, that is, the personnel of utilities should be trained adequately to be able to face extreme weather or catastrophic events (e.g., landslide). Many utilities already have such training or other weather-related emergency plans, but these should be revisited. Training and hiring personnel may increase operational expenses but these expenses may be very little compared to the benefits from the avoidance of a massive destruction of a substation or other related infrastructure.

In addition to personnel, automation of power networks, especially distribution systems, can help in quickly identifying the risky events on the networks. The exact timing of finding a fault may be crucial for the protection of the rest of the equipment. Moreover, use of high voltage DC networks could potentially help in nonpropagating faults in the transmission systems to neighboring utilities. The connection between two AC networks is unstable because of phase differences. Power exchange between two AC networks that are not synchronous is feasible by means of high voltage direct current (HVDC) lines (e.g., England–France). An AC network connected with neighboring grids through HVDC links may, in the worst case, lose the power transmitted over the link in case the neighboring grid goes down. The HVDC transmission will act as a firewall against cascading disturbances (Arrowsmith 2009) and is thus considered as a potential solution for major interconnections.

Overall, it can be concluded that a more extensive use of distributed generation can help in reducing the number of customers affected by an outage and decrease the restoration time. Distributed generation is also considered an essential characteristic of a low carbon energy system and as a result the incorporation of decentralized planning can prove a win–win situation as regards mitigation and adaptation to climate variability.

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3.11 Renewable Energy and Water Resources

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Glossary

Water scarcity An imbalance between water supply and water demand in a given region/community.

Renewable energies Energy that comes from natural resources such as sunlight, wind, waves, tides, and geothermal heat, which are renewable.

Seawater desalination The removal of salts or other constituents through thermal or filtration processes to generate potable water.

Concentrating solar power The harnessing of solar energy by directing/concentrating incoming radiation on a line- or point-collecting device through reflective surfaces.

Cogeneration of electricity and desalinated seawater The generation of electrical energy and potable water in an integrated installation/plant and utilizing renewable/solar energy.

3.11.1 Introduction

Water and energy are two essential ingredients sustaining life on this planet. Both quantities are also intractably linked through a number of critical conditions, particularly when one considers manufactured energy sources and potable water. Examples for these linkages include coolant water needed in electrical power plants or energy required for pumping and transporting drinking water in distribution networks, to name but two (see, e.g., Schnoor 2011; Siddiqi and Anadon 2011). Of course, there are links to other important issues, as well. Water is seen as the primary rate-limiting factor for food production. Electricity

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demand is likely to grow significantly in light of increasing needs for space cooling in order to limit the adverse effects of urban heat island-induced human health problems.

On a more general note, recent decades have seen rapidly increasing multiple pressures on water-, energy-, and food security, an issue that has been described as the Water, Energy and Food Security Nexus (Hoff 2011). The underlying driving forces of this Nexus include a variety of more recent developments including a growing demand on natural resources accompanied by their degradation caused by overexploitation, a rapidly evolving urbanization, and the emergence and growth of Mega Cities, which lead to increasing contaminant emissions and growing volumes of waste products on a limited spatial scale. An ongoing trend toward globalization, particularly in the private sector, with associated tendencies to externalize resource use and degradation to distant regions is another driving force underlying the Water Energy and Food Security Nexus. Finally, exacerbating some of the above drivers, changes in global and regional climate conditions increasingly require mitigation, adaptation strategies, and measures at an accelerating pace. An important characteristic of these pressures is their strong interlinkage, which lead to feedback that drives environmental and human systems to critical thresholds and tipping points that seriously affect access to water, energy, and food.

This chapter concentrates on a subset of the Water, Energy and Food Security Nexus by addressing more specifically the already mentioned linkages between water and energy; that is, the 'Water energy nexus' (see Hoff 2011; Schnoor 2011). In particular, I will consider two issues: (1) electricity generation and its need for water (Figure 1(a)) and (2) the energy demand for seawater desalination, which typically accounts for more than one third of the total cost (Figure 1(b)). Moreover, I will address options and innovative technologies to enable the reduced use of both resources as they relate to issues (1) and (2) above.

The chapter starts out with brief reviews on renewable energy sources (RES) and water availability, water supply, and water demand. This is followed by a concise description of desalination technologies and their recent advance. Next, I concentrate on a novel, but increasingly employed technology to harness solar power in solar-thermal electricity generation: the concentrating solar power (CSP) technology. Finally, I introduce and describe a new technological development that will enable the cogeneration of electricity and desalinated seawater, employing CSP as the ultimate energy source.

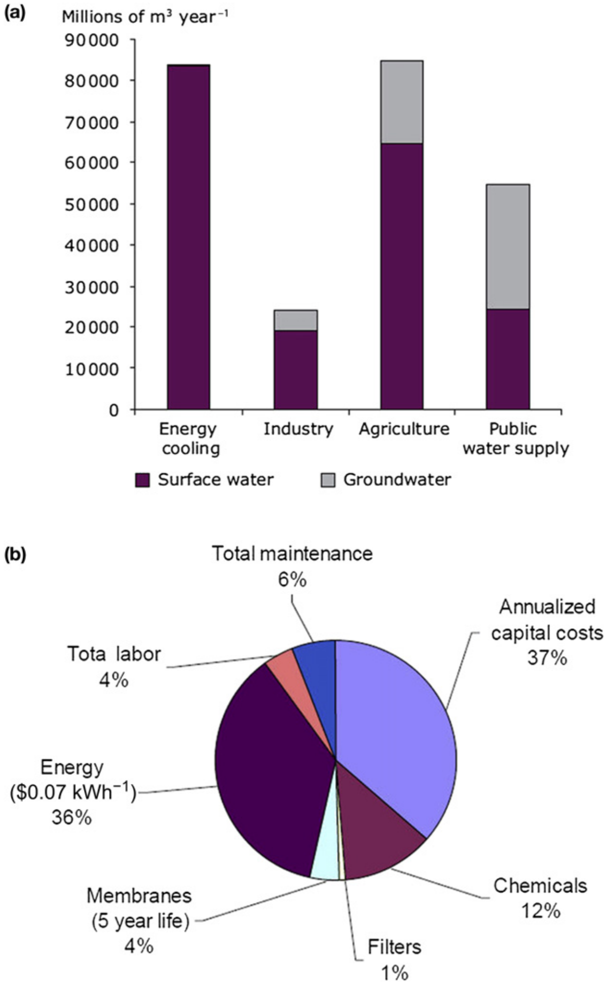


Figure 1 (a) Sources of freshwater abstraction by sector. Source: EEA, 2009: *Water Resources Across Europe – Confronting Water Scarcity and Drought European Environment Agency*, Copenhagen, Denmark, EEA Report, No. 2, 60 pp. [Available online at http://www.eea.europa.eu/publications/water-resources-across-europe.] (b) Annual cost breakdown in a typical American 189 000 m^3 day^{-1} seawater RO plant with conventional pretreatment (b). Source: NAS, 2008: *Desalination: A National Perspective*. National Research Council of the National Academies, Washington, D.C. USA, 254 pp. [Available online at http://www.nap.edu/catalog/12184.html.]

3.11.2 Renewable Energy Sources

Renewable energy sources (RES), for example, wind power, though known throughout the history of humans, represent a relative recent development when it comes to harnessing renewables on an industrial scale. The current use of renewables in the overall global energy portfolio is relatively limited. Renewables (both combustible as well geothermal, solar, wind, etc.) accounted for no more than 10.7% of the total primary energy supply on a global level in 2008 (IEA 2010). The major reason for such a relatively small fraction of renewables lies in the still higher prices of these energies, compared with conventional sources, that is, oil, gas, and nuclear (Figure 2). As can be seen, particularly photovoltaics (PV) comes at a price tag four to five times higher than conventional energies. However, as can be observed as well, prices for onshore wind energies already today come close to conventional prices.

Thus, it is expected that the use of renewable energy sources (RES) will be increasing by significant growth rates over the coming decades. In the European Union (EU), the gross final renewable energy consumption will more than double from 98.7 Mtoe (1 toe equals 41.868 GJ or 11.63 MWh) in 2005 to 2445.6 Mtoe with average growth rates of 6.8 and 6.2 for the periods 2005–10 and 2015–20, respectively (Beurskens and Hekkenberg 2011). In a recent report, the German Advisory Council on the Environment (2011) comes to the conclusion

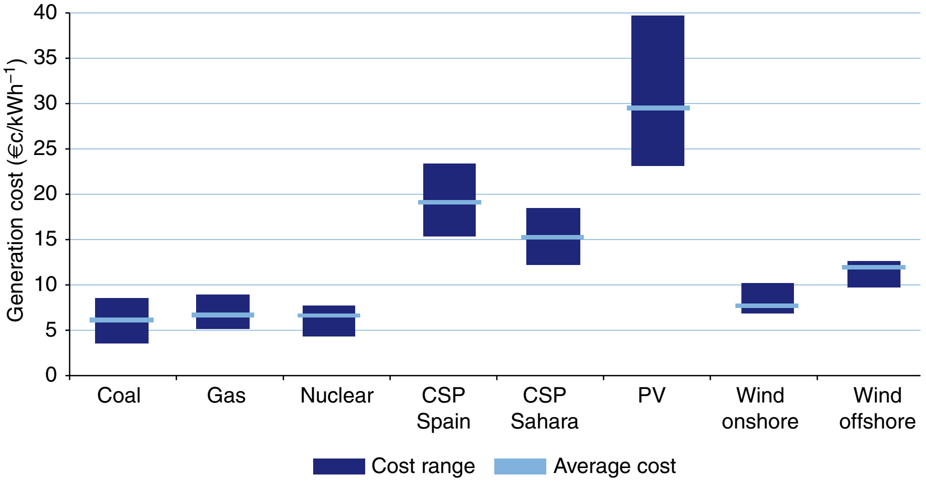


Figure 2 Typical levelized costs of electricity generation. Source: PricewaterhouseCoopers, Potsdam Institute for Climate Impact Research, International Institute for Applied Systems Analysis, and European Climate Forum, 2010: *100% Renewable Electricity – A Roadmap to 2050 for Europe and North Africa*, 144 pp. [Available online at http://www.pwc.co.uk/pdf/100_percent_renewable_electricity.pdf.]

that a secure and affordable wholly renewable electricity supply is well within reach, particularly when combined with enhanced energy efficiency measures.

RES come in different forms and varieties (for an overview on various RES, see, e.g., Beurskens and Hekkenberg 2011; Edenhofer et al. 2011; Schiermeier et al. 2008). In the following, a brief compilation of renewable energy sources with an emphasis of their use for electricity generation will be given.

3.11.2.1 Hydropower

Hydropower harnesses the potential energy of water moving from higher to lower elevations. It is used primarily to generate electricity. Hydropower projects encompass dam projects with reservoirs, run-of-river, and in-stream projects and cover a continuum in project scale (Edenhofer et al. 2011). Hydropower represents the largest source of renewable electricity in Europe, supplying 60% of Europe's total renewable energy. Hydropower technologies are mature and, depending on the location of the installation, hydropower can be cost-competitive even with coal (PricewaterhouseCoopers et al. 2010). Dammed reservoirs for hydropower generation often enable their uses for other purposes including the supply of drinking water, irrigation, flood and drought control, and navigation (Edenhofer et al. 2011).

Because hydropower is a dispatchable form of energy, it is especially important for a renewables-only power system. When combined with pump reservoirs, excess power can be stored for later times, when water supply may be limited. However, two factors limit the major continued expansion of hydropower. First, future capacity is limited by geographic factors and the availability of space for dam storage. This notwithstanding, the economic potential of hydropower is about 30% greater than current utilization and about double the current utilization in western and southeastern Europe, respectively. Second, hydropower utilization is facing significant environmental concerns such as the loss of land, habitat, and the displacement of settlements, which limits its development in many countries.

3.11.2.2 Wind Energy

Wind energy utilizes the kinetic energy of moving air through wind turbines located on land (onshore) or in seawater or freshwater (offshore). Onshore wind energy technologies are proven technologies and are deployed on a large scale. Although offshore wind energy technologies pose significantly larger challenges in their employment, they also have greater potential for continued technical advancement. Electricity generation through wind power is both variable and, to some degree, unpredictable. However, experience and detailed studies from many regions have shown that the integration of wind energy generally poses no insurmountable technical barriers (Edenhofer et al. 2011).

Wind power has been the fastest growing form of renewables in Europe. At the end of 2007, it accounted for 52 GW of installed generating capacity, supplying 3.8% of the EU-27 total electricity consumption. It represents the second largest share of renewable electricity in Europe, after hydropower. One of the major reasons for the growth in wind power utilization is that it is currently the lowest cost renewable energy source (Figure 2). The development of offshore wind installations has been low in comparison with onshore wind, mainly because the costs are, at present, higher than for onshore wind at good sites. It has been estimated that it would be possible to obtain approximately 1000 TWh year^{-1} of onshore wind at a cost of less than €0.05 kWh^{-1}, and about 2500 TWh year^{-1} at a cost of less than €0.07 kWh^{-1} for OECD Europe as a whole. In practice, however, it will not be feasible to develop all of the sites that are suitable for wind power for various reasons (e.g., opposition by the local population). As a consequence of the intermittency of wind, achieving high penetration of wind power would require significant long-distance power transmission lines, spreading local wind conditions over a continental scale (PricewaterhouseCoopers et al. 2010).

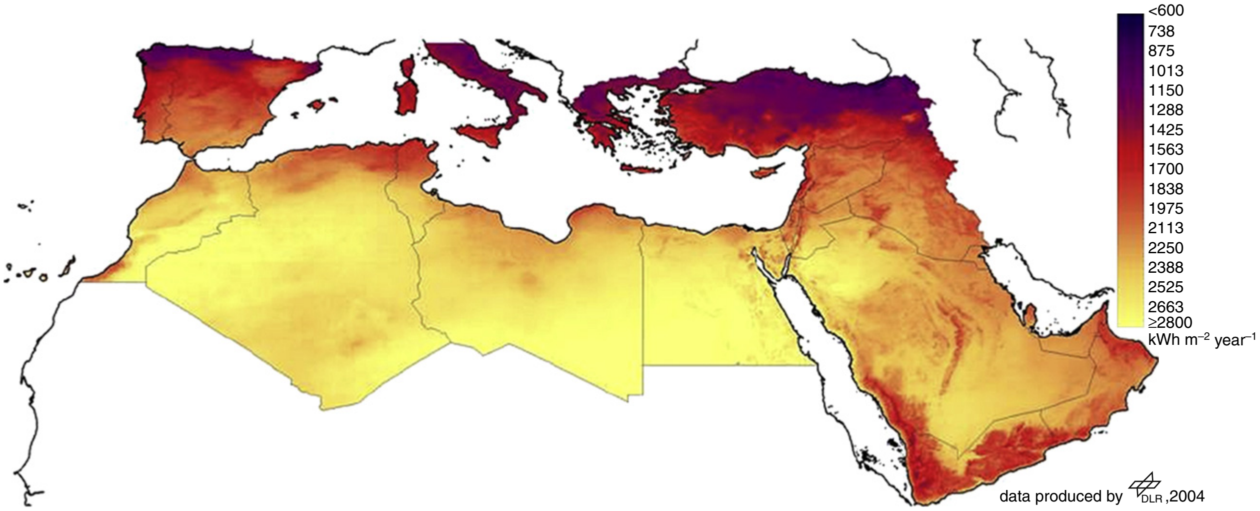


Figure 3 Annual direct solar irradiance in the southern EU-MENA Region. Source: Trieb, F., and Coauthors, 2005: *Concentrating Solar Power for the Mediterranean Region (MED-CSP Study Report)*, German Aerospace Center (DLR), Institute of Technical Thermodynamics Section Systems Analysis and Technology Assessment, Study for the German Ministry of Environment, Nature Conversation and Nuclear Safety, 285 pp. [Available online at http://www.dlr.de/tt/Portaldata/41/Resources/dokumente/institut/system/projects/MED-CSP_Full_report_final.pdf.]

3.11.2.3 Solar Energy

Solar energy technologies harness the energy of solar irradiance to produce electricity. Currently, there are principally two technologies employed: photovoltaics (PV) and concentrating solar power (CSP) technologies. PV generates electricity using the conducting properties of certain chemicals most importantly silicon, through the photo-electric effect. CSP makes use of reflectors to focus sunlight on a small area, in order to generate steam that powers a thermal electric plant (see below for more details). In addition to electricity generation, solar power is employed to produce thermal energy (heating or cooling, either through passive or active means), to meet direct lighting needs and, potentially, to produce fuels that might be used for transport and other purposes. The maturity of solar technologies ranges from the research and development stage (e.g., fuels produced from solar energy), to relatively mature technologies (e.g., CSP), to mature (e.g., passive and active solar heating, and wafer-based silicon PV). Many but not all of the technologies are modular in nature, allowing their use in both centralized and decentralized energy systems. However, particularly CSP technologies achieve economical feasibility only at a power capacity of a few tens of megawatts (see below). Solar energy is variable and, to some degree, unpredictable and solar irradiance varies significantly with geographic location (Figure 3). However, the temporal profile of solar energy output correlates relatively well with energy demands (Edenhofer et al. 2011; PricewaterhouseCoopers et al. 2010).

Photovoltaics has been growing quickly, although it still represents only 9 GW of total capacity in Europe. While in 2002, there were 550 MW of new PV cells installed; in 2007 this capacity had grown to more than 3 GW. PV, however, has two major constraints that somewhat limit its application: the cost of PV cells and the intermittency of solar irradiation and thus power generation. PV currently costs about €0.22–0.39 per kWh (Figure 2), depending on location. Almost all of this is comprised of capital costs. While unit prices for PV cells have been falling and will continue to do so by as much as 50% within a few years, this would still not make PV competitive with other technologies. With regard to the intermittency of PV, power is only generated during daylight and there are no storage options available. Thus, cloudiness and seasonality influence the amount of power generated (PricewaterhouseCoopers et al. 2010).

With regard to CSP, there are several technology variants in use (for more details, see the later section on CSP below). The first commercial plants in operation were built in the United States (410 MW) and Spain (100 MW). Globally, there are now more than 45 new CSP projects under development. These are projected to generate 5000 MW in North America, 2500 MW in Europe, more than 500 MW in North Africa, and 2400 MW elsewhere (PricewaterhouseCoopers et al. 2010).

3.11.2.4 Bioenergy

Bioenergy can be generated from various forms of biomass, including wood, agricultural, and livestock residues; short-rotation forest plantations; energy crops; the organic components of municipal solid waste; and other organic waste streams. Through a variety of processes, these materials can be directly used to produce electricity or heat. They also can be used to create gaseous, liquid, or solid fuels. The range of bioenergy technologies is broad and the technical maturity varies substantially. Bioenergy technologies are being applied in centralized and decentralized settings. The traditional uses of biomass in developing countries (mainly for cooking and heating) are the most widespread current applications. Bioenergy projects usually depend on local and regional fuel supply availability, but recent developments show that solid biomass and liquid biofuels are increasingly traded internationally (Edenhofer et al. 2011).

The burning of biomass for electricity generation can be competitive with coal. When using the resulting waste warmth for district heating, total efficiencies of bioenergy production can reach 85–90%. In combination with district heating, biomass is another dispatchable form of renewable power, because it relies on a storable fuel stock. The main concern with biomass is the availability of fuel stock to sustain large scale utilization. Finding sufficient land and water to grow enough material could become problematic and has been discussed extensively (see, e.g., Edenhofer et al. 2011). In many parts of the world, growing crops dedicated to biomass production can lead to higher net carbon emissions than fossil fuel burning because of the emissions associated with land clearings. There also are concerns about the impact of biomass production on agriculture, water use, and food prices (PricewaterhouseCoopers et al. 2010).

3.11.2.5 Geothermal Energy

Geothermal energy utilizes the accessible thermal energy from the earth's crust. Heat is extracted from geothermal reservoirs using wells ('deep geothermal') or other means including pipes that are deposited close to the surface and heat pumps ('shallow geothermal'). Two basic types of geothermal reservoirs are distinguished: (1) hydrothermal reservoirs, which are naturally sufficiently hot and permeable, and (2) enhanced geothermal reservoirs, which are sufficiently hot but need to be improved with hydraulic stimulation systems (EGS). Once at the surface, fluids of various temperatures can be used to generate electricity or can be used more directly for applications that require thermal energy. This includes (1) district heating or (2) the use of lower-temperature heat from shallow wells for geothermal heat pumps that are used in heating or cooling applications. Hydrothermal power plants and thermal applications of geothermal energy are mature technologies, whereas EGS projects are in the demonstration and pilot phase while also subject to continued research and development. When used to generate electricity, geothermal power plants typically offer constant output (Edenhofer et al. 2011).

While geothermal power has progressed nicely and in some places (such as Iceland) is commercially viable, concerns about the safety of geothermal energy generation have been discussed recently, after geothermal plants apparently triggered local earthquakes in Switzerland and Germany. This calls for additional and thorough studies to be undertaken (PricewaterhouseCoopers et al. 2010).

3.11.2.6 Ocean Energy

Ocean energy is derived from the potential, kinetic, thermal, and chemical energy of seawater, which can be transformed to provide electricity, thermal energy, or potable water. A wide range of technologies are possible, including (1) barrages for tidal range utilization, (2) submarine turbines for tidal and ocean currents, (3) heat exchangers for ocean thermal energy conversion, and (4) a variety of devices to harness the energy of waves and salinity gradients (see, e.g., Frigaard et al. 2008). Ocean technologies, with the exception of tidal barrages, are at the demonstration and pilot project phases and many require substantial additional research and development activities. Some of the technologies have variable energy output profiles with differing levels of predictability (e.g., wave, tidal range, and current), while others may be capable of near-constant or even controllable operation (e.g., ocean thermal and salinity gradient) (Edenhofer et al. 2011).

3.11.3 Water and Water Scarcity

Of all the water on this planet, totaling 1400×10^9 km^3, only 35×10^6 km^3 or 2.5% of it is consumable by humans as potable water. Of this fraction, 68.9% resides as snow, ice, or permafrost in the cryosphere, leaving 31.1% of the freshwater resources (or only 0.78% of the total water on earth) as water accessible to mankind. Despite this apparently small number (i.e., 0.78%), the total accessible freshwater on earth amounts to a quite impressive volume of 10.85×10^6 km^3. However, decades of unsustainable management have led to water shortages that have reached critical levels in many regions of the world (see below). Globally, humans appropriate more than 50% of all renewable and accessible freshwater for their use, while billions still lack the most basic water services highlighting the shortcomings in reaching the UN Millennium Development Goals with regard to the supply of potable water and sanitation (United Nations 2010).

This brings up questions related to the overall supply and the demand for potable water and their spatial and temporal distributions, which will be dealt with in the next section. As already indicated, water scarcity is an issue of increasing importance in some regions of the world and the prospects of climate change tend toward exacerbating these problems. This will be briefly discussed in Section 3.11.3.2.

Although not exclusively so focussed, the following sections will emphasize European conditions and characteristics.

3.11.3.1 Water Availability, Supply, and Demand

While the global volume of available freshwater amounts to 10.85×10^6 km^3, the total freshwater resources across Europe on an annual basis amount to 2270 km^3 year^{-1}. Of this volume, only 13% represent water abstracted from underground aquifers, suggesting that there is sufficient water available to meet demand. This represents only a relatively small proportion of its renewable freshwater resource, which suggests that there is sufficient water available to meet demand (EEA 2009). This notwithstanding, problems of an insufficient supply of potable water arise in many regions: this is in many cases due to an imbalance between water abstraction and availability, which is primarily driven by a mismatch between the distribution of people across Europe and the availability of water. In some locations across Europe, this is exacerbated by excessive abstraction rates.

This is by no means a European problem only. Figure 4 illustrates the availability of freshwater for human consumption on a global level. As can be seen, the volume of drinking water per person and year varies widely, with northern Africa and sub-Saharan Africa representing regions of scarcity, particularly. This reflects to a significant extent the distribution of precipitation on our planet because precipitation represents one of the primary sources of freshwater replenishment.

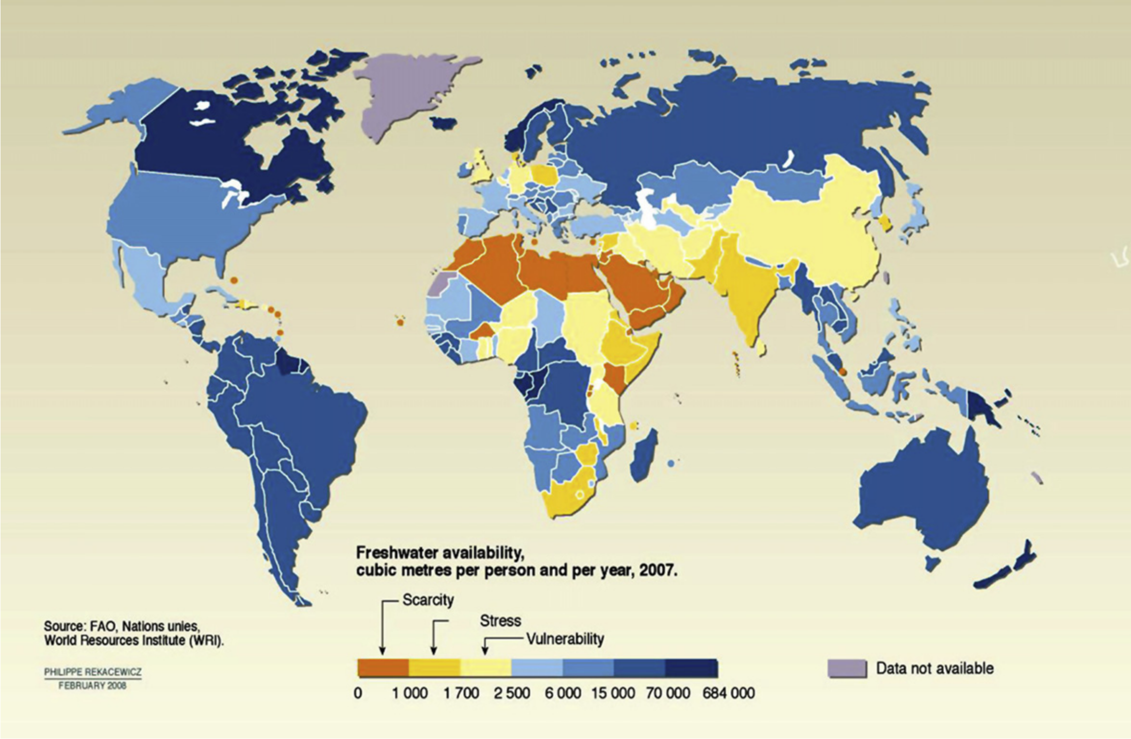


Figure 4 Global freshwater availability for human consumption in 2000. Source: UNEP-GRID, 2008: *Vital Water Graphics, Arendal, Norway.* [Available online at http://www.unep.org/dewa/vitalwater/index.html.]

However, mismanagement, waste, and contamination of freshwater sources in many parts of the world contribute to more rapid exhaustion of available resources than consumption alone.

Sources of freshwater supply include surfacewater and groundwater, water stored in cryospheric reservoirs (snow, ice, and permafrost), and also water produced through seawater desalination, collected rainwater, and reused or processed wastewater. Of the latter, I will only consider desalination in subsequent sections of this chapter.

In Europe, surface water, that is, water in rivers, lakes, and surface reservoirs represents the primary source for the energy and agricultural sectors as well as for industry, whereas groundwater is the predominant source (about 55%) for public water supply owing to its generally higher quality than surface water (Figure 1(a)). For agriculture, however, the role of groundwater as a source is probably underestimated because of illegal abstraction from private wells (EEA 2009). Reservoirs, that is, water bodies created mainly by damming rivers, represent a common means to ensure a sufficient level of water supply particularly in times of prolonged droughts. Even though not in terms of total volume, the sheer number of dams constructed in Cyprus in the 1970s and 1980s reflect the strong desire of the then governments to ensure adequate water security for the country in anticipation of growing demand and decreasing replenishment through precipitation (Figure 5(a)). However, interannual changes in precipitation rates have resulted in varying volumes of water available to the agricultural sector, the main benefactor of the stored dam water in Cyprus (Figure 5(b)).

Water stored in snow and ice is of significant importance for many countries, particularly those at higher latitudes and/or in countries with high mountain ranges that are the precondition for the formation of glaciers and ice caps. The Alps, which have often been called the 'water tower of Europe,' currently provide 40% of Europe's freshwater (EEA 2009). Changes to these stores result in significant impacts on the availability of water, both seasonally and in the longer term.

Groundwater serves as main source of drinking water throughout Europe. However, over-abstraction, contamination by various sources, and intrusion of seawater in coastal aquifers have resulted in significant risks to groundwater resources in many European countries (Figure 6). As can be seen, about 80% of the groundwater is 'at risk' in Cyprus.

However, the future fate of rainfall or precipitation, which represents the principal natural replenishment of surfacewater and groundwater reservoirs, poses a risk of another dimension. One of the principal findings of climate projections, based on numerical global climate models of the Intergovernmental Panel on Climate Change (IPCC), is that regions that are currently well supplied by precipitation are predicted to have increasing rates of rainfall in the coming decades, whereas regions already suffering from decreasing trends of water supply by precipitation are predicted to experience even lesser amounts of rainfall. As simulated in multi-decadal model projections, countries and regions along the mid-latitudinal belts in general and in those of the Mediterranean Basin, in particular, may have changes in regional climate statistics, resulting in significant reductions in precipitation over the coming decades (e.g., Meehl et al. 2007).

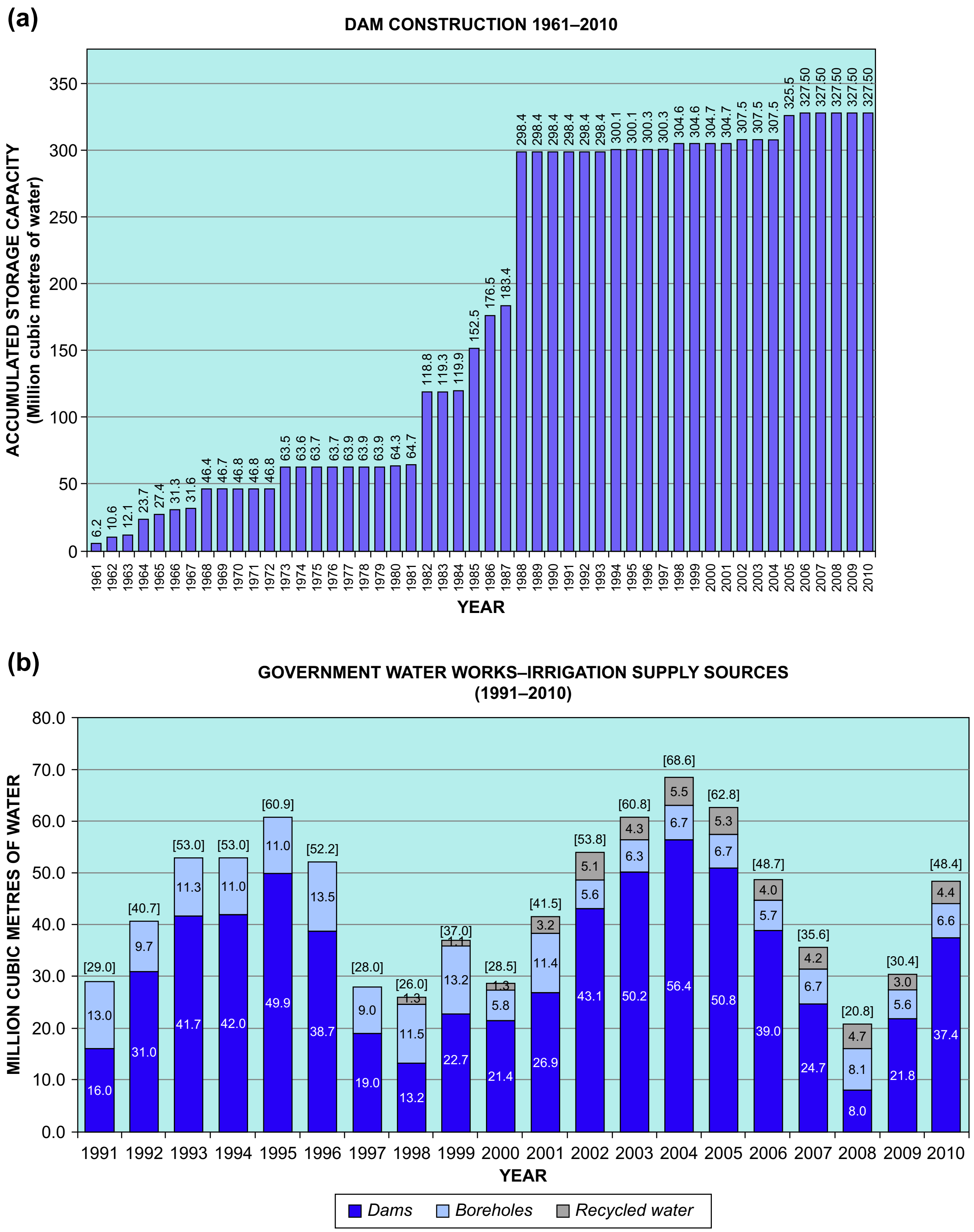


Figure 5 (a) Dam construction in Cyprus and storage volumes to 2010. Source: Water Development Department, Cyprus. (b) Supply of irrigation water from different sources between 1991 and 2010, reflecting mainly the availability of stored water in dams and its variation as a result of changes in annual precipitation. Source: Water Development Department, Cyprus.

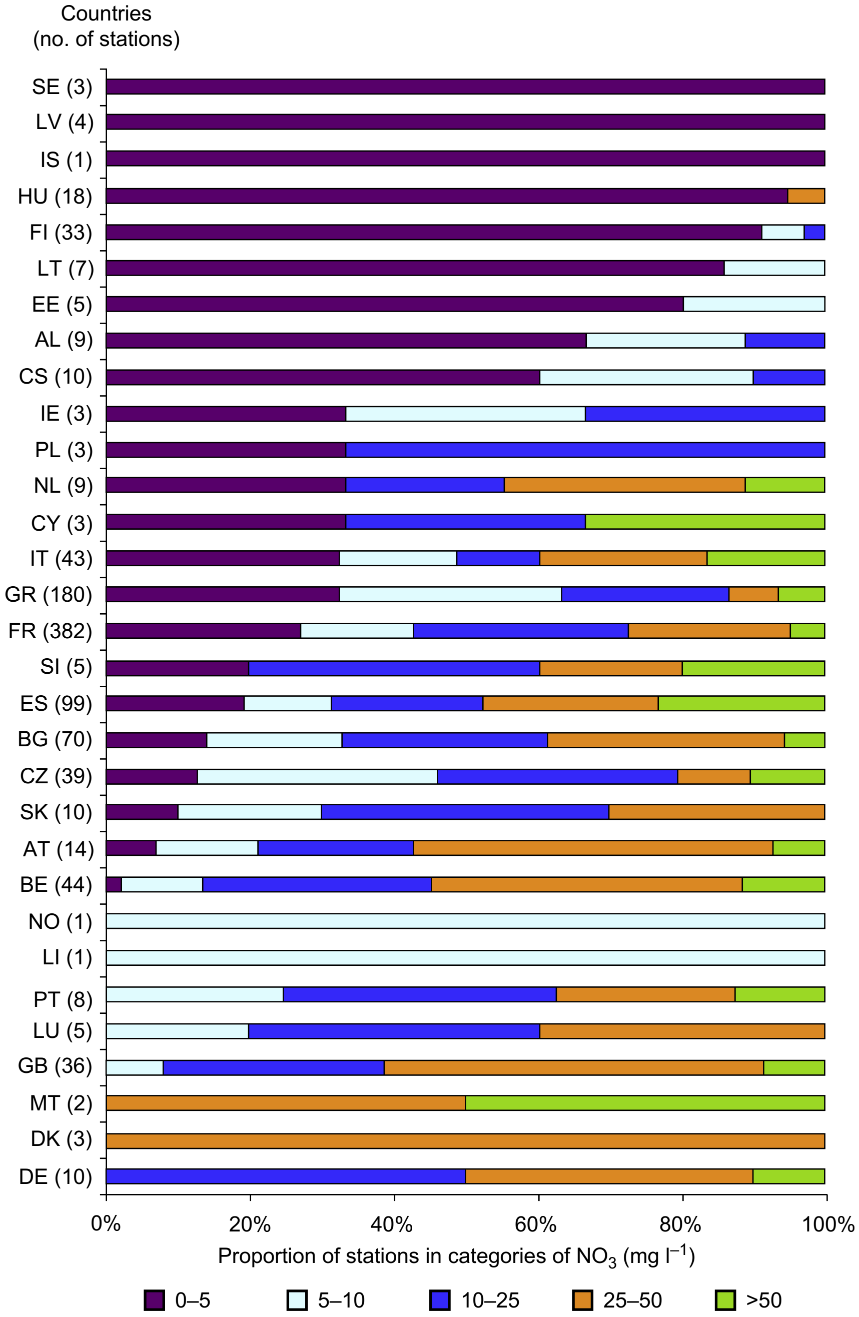
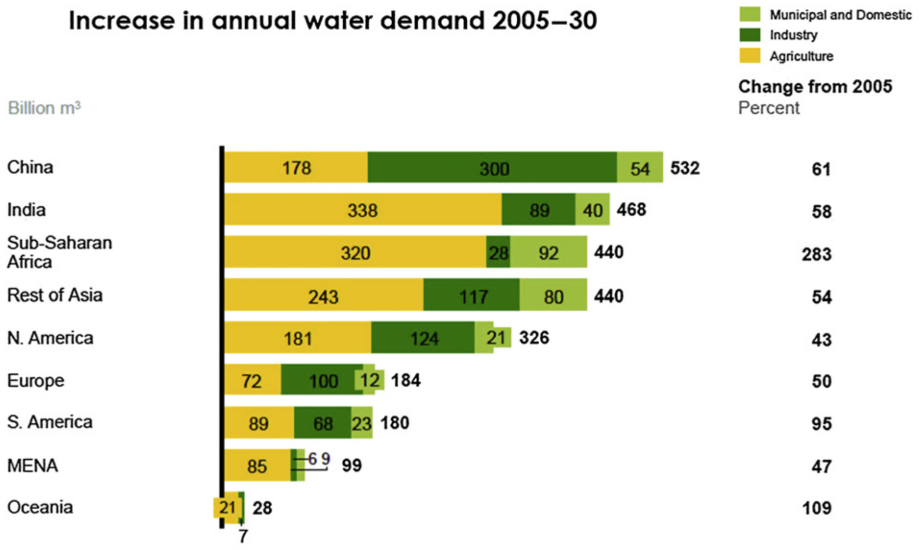


Figure 6 Present concentration of nitrate in groundwater bodies in selected European countries. Source: European Environment Agency, 2008: *Present Concentration of Nitrate in Groundwater Bodies in European Countries.* European Environment Agency. [Available online at http://www.eea.europa.eu/data-and-maps/figures/present-concentration-of-nitrate-in-groundwater-bodies-in-european-countries.]

However, it needs to be recognized that the global climate models have not proved fully satisfactory in multi-decadal predictions of changes in regional climate statistics (see, e.g., Pielke and Wilby 2012). Indeed, even skillfully predicting (in a hindcast mode) regional climate statistics over the last few decades has not been adequately achieved (see, e.g., Anagnostopoulos et al. 2010; van Oldenborgh et al. 2012; Xu and Yang 2012). Fyfe et al. (2011) found that for longer term decadal hindcasts they had to correct for systematic long-term trend biases. Xu and Yang (2012) concluded that without tuning from real world observations, the model predictions are in significant error in terms of both temperature and precipitation. Work by Anagnostopoulos et al. (2010) revealed that local multi-decadal climate model projections do not correlate well with observed measurements, and, moreover, that the correlation at a large spatial scale, for example, the contiguous United States, is even worse than at the local scale.



SOURCE: 2030 Water Resources Global Water Supply and Demand model; baseline agricultural production based on IFPRI IMPACT-WATER base case

Figure 7 Increase in annual water demand for the period 2005–30 in billion cubicmeter and in percent. Source: 2030 Water Resources Group, 2009: *Charting our Water Future – Economic Frameworks to Inform Decision Making*, 198 pp.

With regard to the EU, but also largely reflecting global patterns, the consumption of both surface and groundwater is driven by four main economic activities: cooling in electricity production; public water supply; the manufacturing industry; and agriculture, forestry, and fishing. For the EU, overall consumption patterns amount to 44% of the total abstracted water for energy production, 24% for agriculture, 21% for public water supply, and 11% for industry (Eurostat 2011; c.f., Figure 1(b)). However, there are significant differences in abstraction levels for each of the sectors, depending on geographical and geoclimatic conditions. Figure 7 illustrates increases in water demand in absolute numbers as projected for the period 2005–30 for selected countries/regions of the world (2030 Water Resources Group 2009). As can be seen, water demand will grow substantially in order to satisfy the increasing need of the agricultural and – in the case of China – industrial sectors. Given these figures, in conjunction with what has been said regarding possible changes in regional climate statistics, water scarcity in already water-scarce regions is likely to increase. This will be briefly discussed in the next section.

3.11.3.2 Water Scarcity

The term 'water scarcity' is defined by the UN-Water initiative as "… the point at which the aggregate impact of all users impinges on the supply or quality of water under prevailing institutional arrangements to the extent that the demand by all sectors, including the environment, cannot be satisfied fully. Water scarcity is a relative concept and can occur at any level of supply or demand. Scarcity may be a social construct (a product of affluence, expectations, and customary behavior) or the consequence of altered supply patterns – stemming from climate change for example …" (UN-Water 2005). More 'practical' definitions of this and related terms are given in the Human Development Report 2006 (United Nations Development Programme 2006): water stress depicts the availability of less than 1700 m^3 per person and year, water scarcity of less than 1000 m^3 per person and year and absolute water scarcity of less than 500 m^3 per person and year.

If the related subset of the current IPCC climate change projections is correct (Meehl et al. 2007), almost half of the world's population will be living in areas of high water stress by 2030, including between 75 million and 250 million people in Africa. In addition, water scarcity in some arid and semiarid places would displace between 24 million and 700 million people (UN-Water).

Information in the Human Development Report (United Nations Development Programme 2006) confirms this projection. The report indicates that by 2050 about 5.5 billion people will suffer from either water stress or water scarcity.

The current situation with regard to the global distribution of water stress and waters scarcity is depicted in Figure 4. As can be seen, all of the northern African countries and most of the Middle Eastern countries (including Cyprus) suffer from water scarcity or water stress. As a remedy to secure the supply of drinking water to their citizens, many of the aforementioned countries have introduced seawater desalination in recent years. Some countries, for example, Cyprus (Water Development Department Cyprus 2010) and Israel, are determined to secure the entire demand for potable water through desalination of seawater (in the following abbreviated as DSW). The next section will briefly describe the current state of DSW technologies, their energy demands, and some of the new developments.

3.11.4 Desalination of Seawater

In light of the discussions that follow, we will concentrate on two classes of desalination, that is, membrane-based methods, specifically the Reverse Osmosis (RO) technology, and thermal desalination methods, specifically multiple effect distillation

(MED). For a more general overview see, for example, NAS (2008) or Trieb et al. (2007).

3.11.4.1 Brief Review of RO and MED Desalination Technologies

3.11.4.1.1 Multieffect Desalination

A multieffect desalination (MED) evaporator consists of several consecutive cells (effects) maintained at decreasing levels of pressure (and temperature) from the first (hot) cell to the last one (cold). Each cell mainly consists of a tubes bundle. The top of the bundle is sprayed with the seawater make-up that then flows down from tube to tube by gravity. Heating steam is introduced inside the tubes. Since tubes are cooled externally by make-up flow, steam condenses into distillate (freshwater) inside the tubes. At the same time, seawater warms up and partly evaporates by recovering the condensation heat (latent heat), because of the fact that evaporating seawater slightly concentrates when flowing down the bundle and gives brine at the bottom of the cell. The vapor raised by seawater evaporation is at a lower temperature than the heating steam. However, it can still be used as heating media for the next effect whereby the process is repeated. The decreasing pressure from one cell to the next one allows brine and distillate to be drawn to the next cell, wherein they will flash and release additional amounts of vapor at the lower pressure. This additional vapor will condense into distillate inside the next cell. This process is repeated in a series of effects. In the last cell, the produced steam condenses on a conventional shell-and-tube heat exchanger. This exchanger, called 'distillate condenser,' is cooled by seawater. At the outlet of this condenser, part of the warmed seawater is used as make-up of the unit; the other part is rejected to the sea. Brine and distillate are collected from cell to cell until the last one, from where they are extracted by centrifugal pumps.

The main advantages of a MED system can be summarized as follows:

- Very low electrical consumption (<1.0 kWh m^{-3})
- Operates at low temperature (<70 °C) and at low concentration (<1.5)
- Produces steadily high purity distillate
- Does not need complex pretreatment of seawater and are tolerant to variations of seawater conditions
- Is highly reliable and simple to operate
- Reduces civil works cost
- Is simple to install
- Has a low maintenance cost
- Operates 24 h a day with minimum supervision
- Ideal for coupling with power plants
- Can be adapted to any heat source
- Allows very high thermal efficiencies and savings in fuel costs (NAS 2008)

If high-pressure steam is available, for example, from a power plant, the efficiency of a MED plant can be further enhanced by using a steam ejector. The high-pressure steam is the so-called motive steam, which provides the energy for recompression of the product vapor from the evaporator of a given effect. The vapor leaving the thermocompressor, which will be at an intermediate pressure level, is again used as driving heat for the first evaporator. A MED with thermal vapor compressor can benefit from heat at higher temperatures, without increasing the top brine above the critical scaling temperature of 65–70 °C. There are very simple and robust skid mounted units with smaller size steam piping available. However, MED-TVCs have a lower thermodynamic efficiency than a simple MED. A steam transformer is mandatory if clean distillate in the first cell is required. Recently, steam compressors with low motive steam pressure (1–2 bar abs.) have been developed. All systems are quite robust. The operation is simple and fault tolerant to a very high degree.

3.11.4.1.2 Reverse Osmosis

The reverse osmosis (RO) technology is based on a membrane separation process in which the water from a pressurized saline solution is separated from the solutes (the dissolved material) by flowing through a membrane. In practice, the saline feed water is pumped into a closed vessel where it is pressurized against the membrane. As a portion of the water passes through the membrane, the remaining feed water increases in salt content. At the same time, a portion of this feed water is discharged without going through the membrane.

Without this controlled discharge, the pressurized feed water would continue to increase in salt concentration creating problems such as precipitation of super saturated salts and increased osmotic pressure across the membranes.

An RO system is made up of the following basic components:

- Pretreatment
- High-pressure pumps
- Membrane assembly and
- Posttreatment

The past 10 years have been significant ones for the RO process. Although the process has not fundamentally changed in concept, there have been steady and continuous improvements in the efficiency of the membranes, energy recovery, energy reduction, membrane life, control of operations, and operational experiences. Currently most of implemented seawater desalination plants use RO technology. Systems of 300 000 m^3 day^{-1} and recently even larger have been built and are in operation in many parts of the world. Desalted water cost decreased from \$2.0 to 0.5 m^{-3} and worldwide capacity is continuously increasing (Trieb et al. 2009; UNEP/MAP/MED POL 2003).

3.11.4.2 Energy Demand for Desalination

Seawater desalination, regardless of the technology employed, is a relatively energy intensive process. This is why desalination costs are strongly correlated with energy prices (NAS 2008).

Energy requirements for desalination plants depend on the following:

- Volume of water produced
- Salinity and temperature of the feed water
- Quality of the water produced
- Desalination technology used

In the following, I will present brief estimates for the energy needs of MED and the RO technology, respectively.

3.11.4.2.1 Energy Demands for MED

Semiat (2008) provides a comprehensive review of the energy requirements for MED technologies. The simplest desalination technique, single-stage evaporation of seawater, consumes a tremendous amount of energy, around 650 $kWh_t\ m^{-3}$ of product, depending slightly on the evaporation temperature (the unit kWh_t refers to thermal energy). The MED technology has overcome this obstacle by reusing energy consumption through multiple stages (see above). Thermal energy based on fuel consumption in typical 'single-purpose' plants is in the range of 40–65 $kWh_t\ m^{-3}$ of product for MED, and the work equivalent of these energy consumptions, based on an efficiency of about 45% in a modern power station, is 18-30 $kWh_e\ m^{-3}$. Around 1.2–4.5 $kWh_e\ m^{-3}$ of pumping energy must be added to these quantities. In his review, Semiat (2008) presents numbers on the combined energy demand of MED plants ranging from 6–12 to 5–65 $kWh_e\ m^{-3}$ as given by different authors.

The energy consumption of thermal desalination processes may be reduced considerably in 'double-purpose' plants, which utilize heat released by the turbine condensing steam to provide the primary thermal energy required for a MED desalination process. Because high efficiency of electrical energy production requires a low steam condensation temperature close to the ambient temperatures, the back-pressure of the turbine is consequently increased to provide an adequate heating steam temperature in the range of 70–120 °C. Given this alternative, the total energy consumption for MED technologies that utilize exiting steam at various temperatures and including pumping energies in the process amounts to

- 4–5.6 $kWh_e\ m^{-3}$ for a GOR (GOR or 'gained output ratio' is defined as the ratio of the number of tons of water produced per ton of steam as energy invested) of 10 and a temperature working range of exiting steam of 70–35 °C
- 5 $kWh_e\ m^{-3}$ for a GOR of 16 and a temperature working range of exiting steam of 100–35 °C (Semiat 2008).

The estimation given appears to be too low because energy losses to the environment may be high and may be altered based on the heat recovery equipment employed and thus the capital investment needed in building the plant. This results in total energy consumption closer to 13 $kWh_e\ m^{-3}$ including pumping, and the real values probably lie between this and the values given above (Semiat 2008).

3.11.4.2.2 Energy Demands for RO

Owing to the development of large pumps that use modern efficient turbines and other energy recovery devices and thereby achieve efficiencies approaching approximatly 90%, the specific energy for RO desalination has decreased significantly over the past decade and is approaching the theoretical thermodynamic minimum. The newer devices, known as turbochargers, pressure exchangers, or work exchangers, names adopted by different manufacturers, represent efficient ways of recovering the energy content of the high-pressure concentrate leaving the membrane module (Semiat 2008). The turbines convert the concentrate pressure into the velocity of a jet that spins a wheel, which is used either to reduce the power consumption of the motor driving the pump or to boost the pressure of the feed to a second stage. Taking into account the additional pumping requirements involved in conveying the feed, concentrate, and permeate steam, the overall energy needs are less than 3.7 $kWh_e\ m^{-3}$ of product in RO seawater desalination (Semiat 2008).

Thus, the overall energy requirements appear to be much less for RO plants in comparison with MED plants. However, as explained above, MED technologies enable the utilization of process or waste heat from other processes, for example, electricity generators, which favor MED over RO when considering the coupling of electricity generation and seawater desalination. This will be described in more detail later. However, before addressing this issue, the following section presents a review of solar-thermal electricity generation.

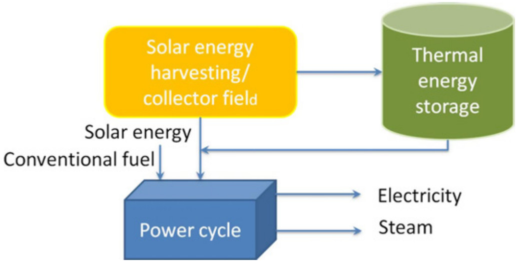


Figure 8 Main elements and principle of a CSP plant. Source: After Trieb, F., and Coauthors, 2009: *Combined Solar Power and Desalination Plants: Techno-Economic Potential in Mediterranean Partner Countries – WP1: Technology Review and Selection of CSP and Desalination Configurations adapted for Application in the Southern and Eastern Mediterranean Region*; Final Report, 117 pp.

3.11.5 Concentrating Solar Power

3.11.5.1 General Principles

Concentrating solar power (CSP) plants represent solar-thermal facilities for electricity generation. They combine the capability of a thermal energy storage medium with alternative hybrid operations employing either solar energy harvested or fossil or biofuels (Figure 8). This enables – at least theoretically – the provision of electrical power on demand, 24 h a day and 365 days a year. The core element of a CSP plant is a field of large mirrors reflecting the captured solar rays to a small receiver element, thus concentrating the solar radiation intensity by about 80 to several 100 times and producing high temperature heat at several 100 to over 1000 °C. This heat can be either used directly in a thermal power cycle based on steam turbines, gas turbines, or Stirling engines, or accumulate in a heat storage medium such as molten salt, concrete, or phase-change material to be delivered at a later point to the power cycle for nighttime operation (see the following).

The principle of operation of a concentrating solar collector and of a CSP plant is given in Figure 8, which illustrates both the hybrid operation option of a CSP plant with solar and other energy and the option of either using the energy harvested directly in the power cycle or to transfer it to the heat storage device. Related to the typical requirements of a grid operator, CSP plants can be considered similar to any conventional fuel-fired power station, but with less or no fuel consumption. Therefore, CSP plants represent important elements for maintaining grid stability and control in future electricity supply systems based mainly on renewable energy sources. CSP plants can have capacities from 5 to several 100 MW of electricity generation (Trieb et al. 2009).

One of the benefits of CSP power plants is the fact that the steam turbines usually used for power generation provide an excellent spinning reserve: Such a reserve is very important for short-time compensation of any failures or outages within the electricity grid. Spinning reserves can only be provided by rotating generators such as steam or gas turbines. Moreover, the flexible design of CSP plants allows them to operate in all load segments from base-load and intermediate-load to peak-load services, just as often required by grid operators (Trieb et al. 2009).

A major advantage of the CSP technology is illustrated in **Figure 9**. The figure illustrates a simulated time series of one week of operation of equivalent wind, PV, and CSP systems with 10 MW installed power capacity each at Hurghada, Egypt. As can be seen, whereas wind and photovoltaic power systems deliver fluctuating power and either allow only for intermittent solar operation or require considerable conventional backup, a concentrating solar power plant can deliver stable and constant power capacity because of its thermal energy storage capability and to the possibility of hybrid operation with fuel (Trieb et al. 2009).

To cover a constant load or to follow a changing load by wind or PV electricity would additionally require the electricity grid and conventional plants for external backup. In both cases, an additional backup capacity would have to be installed and operated for most of the time, generating a relatively small portion of electricity during daytime and wind periods, but full capacity during night and periods without significant wind. In our example, the renewable share provided by CSP is about 90%, that of PV is 25%, and that of wind power is about 35–40%. Depending on varying conditions at different locations, these numbers also can be considered as typical for the average annual renewable share of such systems (Trieb et al. 2009).

As a consequence, CSP plants can save more fossil fuel and replace more conventional power capacity compared with other renewable energy sources such as PV and wind power. Theoretically, instead of conventional backup power or fuel, electricity generated by all three systems could be stored in batteries, pump storage, or hydrogen energy storage in order to

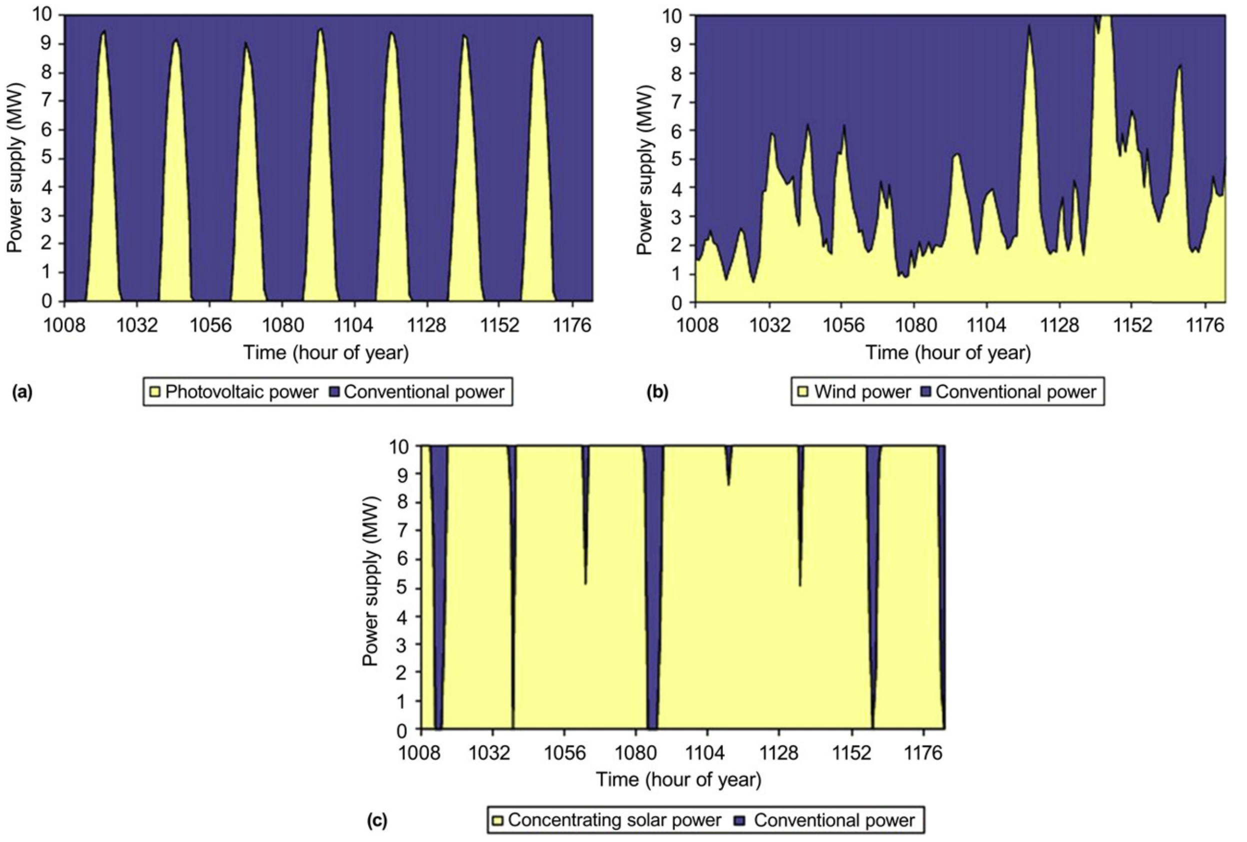


Figure 9 Power supplied by 10 MW capacity (**a**) PV, (**b**) wind, and (**c**) CSP plant (all in yellow) and conventional backup power from the grid (in blue) needed to provide constant 10 MW base load supply, simulated for solar irradiation and wind conditions in Hurghada, Egypt. Source: Trieb, F., and Coauthors, 2009: *Combined Solar Power and Desalination Plants: Techno-Economic Potential in Mediterranean Partner Countries – WP1: Technology Review and Selection of CSP and Desalination Configurations adapted for Application in the Southern and Eastern Mediterranean Region; Final Report*, 117 pp.

provide continuous power capacity. In that case, the additional electrical storage capacities needed by CSP would be rather small, whereas significant storage would be required for PV and wind power, prohibitively increasing the overall system cost and energy losses (Trieb et al. 2009).

A reasonable economic performance of concentrating solar power plants is reached at an annual direct solar irradiance of more than 2000 kWh m^{-2} $year^{-1}$. The economic potential of CSP in Europe has been assessed in Trieb et al. (2005). It is limited to Spain, Portugal, Greece, Turkey, and the Mediterranean Islands and amounts to 1580 TWh $year^{-1}$, of which 1280 TWh $year^{-1}$ are located in southern Spain. Although there is a relatively large CSP potential in Europe, more attractive sites are located south of the Mediterranean Sea with an annual direct solar irradiance of up to 2800 kWh m^{-2} $year^{-1}$.

For concentration of the incoming sunlight, most systems use curved or flat glass mirrors because of their very high reflectivity. Point focusing and line focusing collector systems are used, as shown in Figure 10. These systems can only use the direct portion of solar radiation, but not its diffuse component, which cannot be concentrated by mirrors. Line focusing systems are easier to handle than point concentrating systems, but have a lower concentration factor and hence achieve lower temperatures than point focusing systems. Therefore, line concentrating systems will typically be connected to steam cycle power stations, whereas point concentrating systems are additionally capable of driving gas turbines or combustion engines (Trieb et al. 2009).

More details to these and additional CSP technologies can be found in Trieb et al. (2009). In the following, I will briefly describe the three technologies depicted in Figure 10 in more detail.

3.11.5.2 Brief Review of Major Types of CSP Technologies (This section is largely based on Trieb et al. (2009))

3.11.5.2.1 Parabolic Trough Collectors for Steam Cycle Power Plants

3.11.5.2.1.1 Parabolic Trough Collector with Synthetic Heat Transfer Fluid Some line focusing systems use parabolic trough mirrors and specially coated steel absorber tubes to convert sunlight into useful heat (cf. Figure 10). The troughs are normally designed to track the sun along one axis, predominantly north–south. To generate electricity, a fluid flowing through the absorber tube – usually synthetic oil or water/steam – transfers the heat to a conventional steam turbine power cycle. Concentrating the sunlight by about 70–100 times, typical operating temperatures are in the range of 350–550 °C. Plants of 200 MW rated power and more can be built with this technology.

In order to increase the number of solar operating hours beyond the times when the sun shines, the collector field can be designed to provide, under standard conditions, more energy than the turbine can accept. This surplus energy is used to charge a heat storage medium, which can provide the required energy input to the turbine system during periods of insufficient solar radiation (see below).

The experience of parabolic trough steam cycles dates back to 1985, when the first of a series of nine solar electricity generating systems (SEGS) was commissioned in California, with a rated capacity between 14 MW (SEGS I) and 80 MW (SEGS IX, commissioned in 1991). The plants have been run

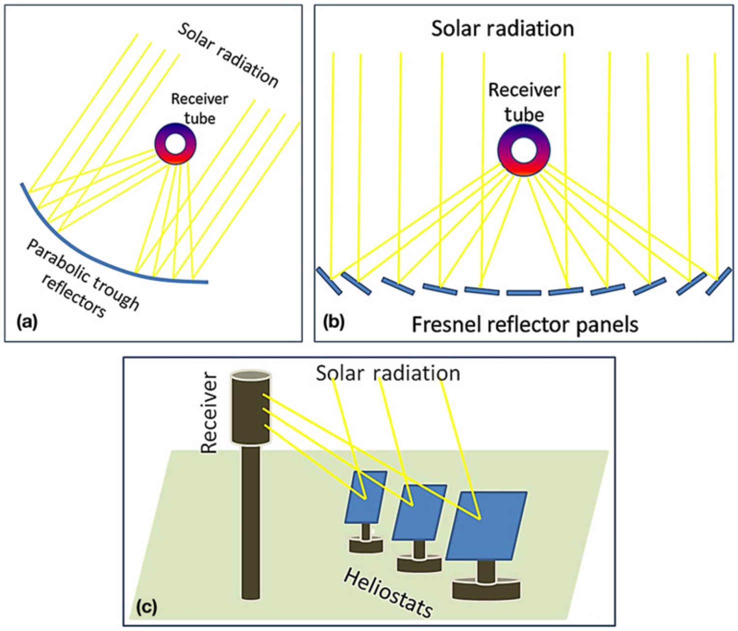


Figure 10 Major elements and principles of the three principle CSP technologies: (**a**) Parabolic trough technology, (**b**) linear Fresnel technology, and (**c**) point concentrator technology (dish-Stirling engines are not shown here).

successfully since then, producing more than 15 000 GWh of solar electricity up to now (for more details, see Trieb et al. 2009, 2005).

3.11.5.2.1.2 Parabolic Trough for Direct Steam Generation

The present parabolic trough plant design uses a synthetic oil to transfer energy to the steam generator of the power plant cycle. Direct solar steam generation in the absorber tubes of parabolic trough collectors is a promising option for improving the economy of solar thermal power plants (Eck and Steinmann 2005), because all oil-related components become obsolete and steam temperature (and hence efficiency) can be increased. First tests have demonstrated the technical feasibility of this technology (Trieb et al. 2009).

3.11.5.2.2 Linear Fresnel Collectors for Steam Cycle Power Plants

Instead of singular parabolic troughs, newer developments have employed a number of horizontal reflector elements that can be controlled individually (cf. Figure 10); they have been labeled linear Fresnel systems. In a Fresnel system, the parabolic shape of the trough is split into several smaller, relatively flat segments. These are put on a horizontal rack and connected at different angles to a rod-bar that moves them simultaneously to track the sun during the day. Because of this arrangement, the absorber tube can be fixed above the mirrors in the center of the solar field, and does not have to be moved together with the mirror during sun tracking.

Such linear Fresnel systems have recently been developed in order to employ a simpler design at lower cost than the parabolic trough technology; for example, linear Fresnel collector systems show a weight reduction per unit area of about 75% relative to parabolic troughs. On the other hand, the simple optical design of the Fresnel system leads to a lower optical efficiency of the collector field, requiring about 33–38% more mirror aperture area for the same solar energy yield compared with the parabolic trough. First prototypes realized up to now show promising results, and first power plants are presently in the design phase.

With regard to the environmental impacts of a given solar field, Fresnel systems have considerable advantages over parabolic troughs. Land use requirements are much lower, as the distances between mirrors are much smaller. The collector aperture area covers between 65 and 90% of the required land, whereas for a parabolic trough, only 33% of the land is covered by mirrors, because the distances between the single parabolic-trough-rows required to avoid mutual shading are considerable. Considering the lower optical efficiency of the Fresnel system (i.e., about 66% of that of a parabolic trough system), linear Fresnel systems attain a solar energy yield per square meter of land about twice that of a parabolic trough system.

3.11.5.2.3 Central Receiver Systems for Steam Cycle Power Plants

The most common form of central receiver system is solar power towers. They consist of an array of dual-axis tracking reflectors (heliostats) that concentrate light on a central receiver at the top of a tower where it usually raises the temperature of a heat transfer fluid (water or oil) to significant temperatures of between 500 and 1000 °C. This fluid is subsequently used as a heat source for a power generation or energy storage system.

Heliostats are devices that consist of one or more mirrors, usually plane ones, which can be individually controlled and moved in order to keep reflecting sunlight directed toward the central receiver, thus compensating for the sun's apparent motions in the sky. In almost every case, the target is stationary relative to the heliostat, so the light is reflected in a fixed direction.

Despite the fact that power-tower developments are somewhat less mature compared with parabolic trough systems, they offer higher efficiency and better energy storage capability. As of now, an increasing number of experimental but also commercial systems have been erected. The Solar Two in Dagget, California, USA, and the Planta Solar 10 (PS10) in Sanlucar la Mayor, Spain, are representative examples of this technology.

The PS10 is comprised of 624 heliostats; each one with a mobile 120 m^2 curved reflective surface mirror. The receiver is designed to produce saturated steam at 250 °C from thermal energy supplied by concentrated solar radiation. The thermal power received by the receiver is about 55 MW at full load. The system has a saturated water thermal storage with a capacity of 20 MWh. A part of the steam produced is used to load the thermal storage system during the full load operation of the plant.

3.11.5.3 Heat-Storage Technologies

3.11.5.3.1 Principles of Heat Storage

The option of heat storage is one of the most distinguishing features of CSP power plants in comparison with other renewable energy technologies such as wind power or photovoltaics. It allows the generation of electricity on demand similar to plants driven by fuel oil or natural gas, despite the fact that CSP plants are based on fluctuating solar energy resources. This represents a very important option that allows increasing the revenues from power sales, because off-peak solar energy from the morning hours can be shifted to the evening on-peak electricity demand, when sales prices may be a factor of two or three higher than in the off-peak hours.

If CSP plants are utilized for seawater desalination, as well (see below), the continuous operation of the desalination plants – either as reverse osmosis plant or through thermal desalination – is crucial in order to avoid scaling and biofouling, which would occur immediately if plants would be left idle.

Employing heat storage in CSP plants has for long been considered a major advantage of this technology and a significant body of experience has been accumulated globally over the last decades (Figure 11). Various technologies and media have been developed and employed in heat storage. The direct storage of heat in synthetic-oil heat transfer fluid (HFT) and molten salt as storage media have been investigated and utilized in the power industry since the 1980s and can thus be considered as fully commercial. However, because the use of HTF as a storage medium is considered too costly, molten salt has been developed to maturity and is currently applied in several CSP plants in Spain.

However, in addition to these well-established technologies, new storage concepts based on concrete and phase-change material are presently under investigation. These, along with

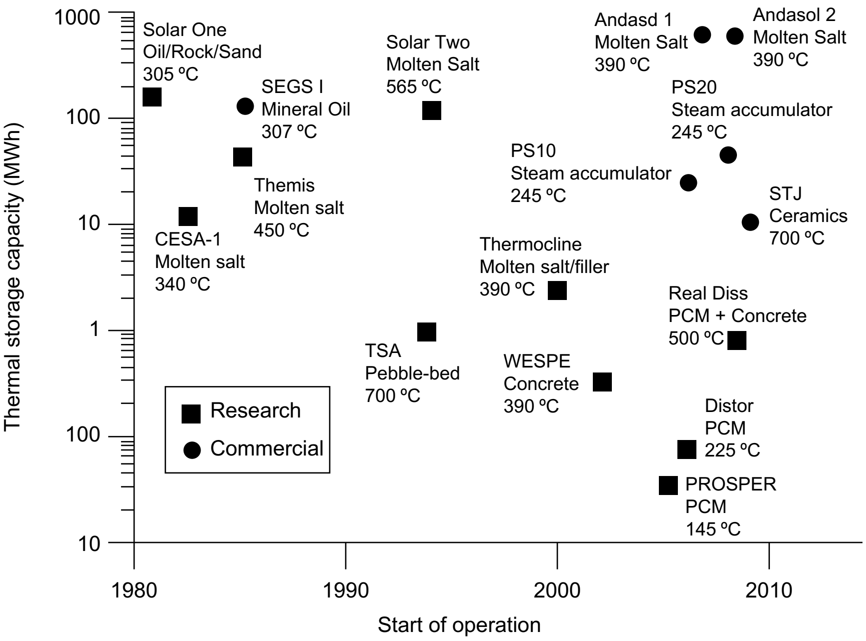


Figure 11 Experiences gained in employing energy storage in CSP plants over the last three decades. Source: Zunft, S., D. Laing, and R. Tamme, 2008: Speicher für Solare Turmkraftwerke, 11. Sonnenkolloquium 2008 "Solare Turmkraftwerke," Cologne, Germany.

the aforementioned established technologies will be described in more detail in the sections that follow.

3.11.5.3.2 Sensible Heat Two-Tank Molten Salt Storage

Molten salt is a medium often used for industrial thermal energy storage. It is relatively cost effective, nonflammable, and nontoxic. The most common molten salt is a binary mixture of 60% sodium nitrate ($NaNO_3$) and 40% potassium nitrate (KNO_3). During operation of the CSP plant, the mixture is maintained at 290 °C in the cold storage tank, and can be heated up to 565 °C. Two-tank storage systems are very efficient, with about 1–2% thermal loss over a one day storage period. Because the molten salt mixture freezes at temperatures at or below about 230 °C (depending on the composition of the salt), care must be taken to prevent it from freezing at night, especially in any of the piping systems. This would lead to irreparable damage to the heat storage installation at the plant and therefore is usually prevented by applying heating by external sources.

Heat exchangers are used to transfer the thermal energy from the heat transfer fluid warmed up by the solar field to the hot tank. During discharge, the heat transfer fluid is circulated through the same heat exchangers to extract the heat from the storage medium and transfer it to the solar steam generator of the power plant. The cost of investment of a two-tank molten salt system amounts to about €40–60 kWh^{-1}.

3.11.5.3.3 Sensible Heat Concrete Storage

A sensible heat storage system using concrete as storage material has been developed by the Ed. Züblin AG and the German Aerospace Center (DLR), Germany. A major motivation for employing this material is the significant cost reduction of the heat exchanger and the high temperatures that concrete storage material can withstand. For live-cycle tests and additional improvements of the original design, a 20 m^3 solid media storage test module was built and thermally cycled through an electrically heated thermal oil loop. The solid media storage test module has successfully accumulated about 1 year of operation in a temperature range between 300 and 400 °C. Investments needed for this technology amount to about €30–40 kWh^{-1} at present prices with a medium term cost target of €20 kWh^{-1}.

3.11.5.3.4 Latent Heat Phase-Change-Material Storage

Latent heat phase-change-material (PCM) storage technologies represent relative recent developments. A major technical challenge for a successful implementation of high-temperature latent heat storage systems is the insufficient thermal conductivity of the available phase-change materials of around 0.5 $W(m\,K)^{-1}$. During the discharge process, the energy released by solidification of the storage material must be transported from the solid–liquid interface through the growing solid layer to the heat exchanger surface, which is slowed down by the low thermal conductivity of the solid PCM.

Enhanced heat exchange has been achieved through the use of fins attached vertically to the heat exchanger tubes within the storage material. Fins can be manufactured of graphite foil, aluminum, or steel. High-temperature latent heat storage technologies with high-capacity factors have been demonstrated at different temperature levels. The sandwich concept using fins made either from graphite or aluminum has proved to be the best option to realize cost-effective latent heat energy storage. The application of graphite is preferred for applications up 250 °C; at higher temperatures aluminum fins are used.

PCM test storage facilities with a capacity of approximately 700 kWh are currently being manufactured. Research activities aim at the thermoeconomic optimization of the storage concept; further storage systems using the sandwich concept are

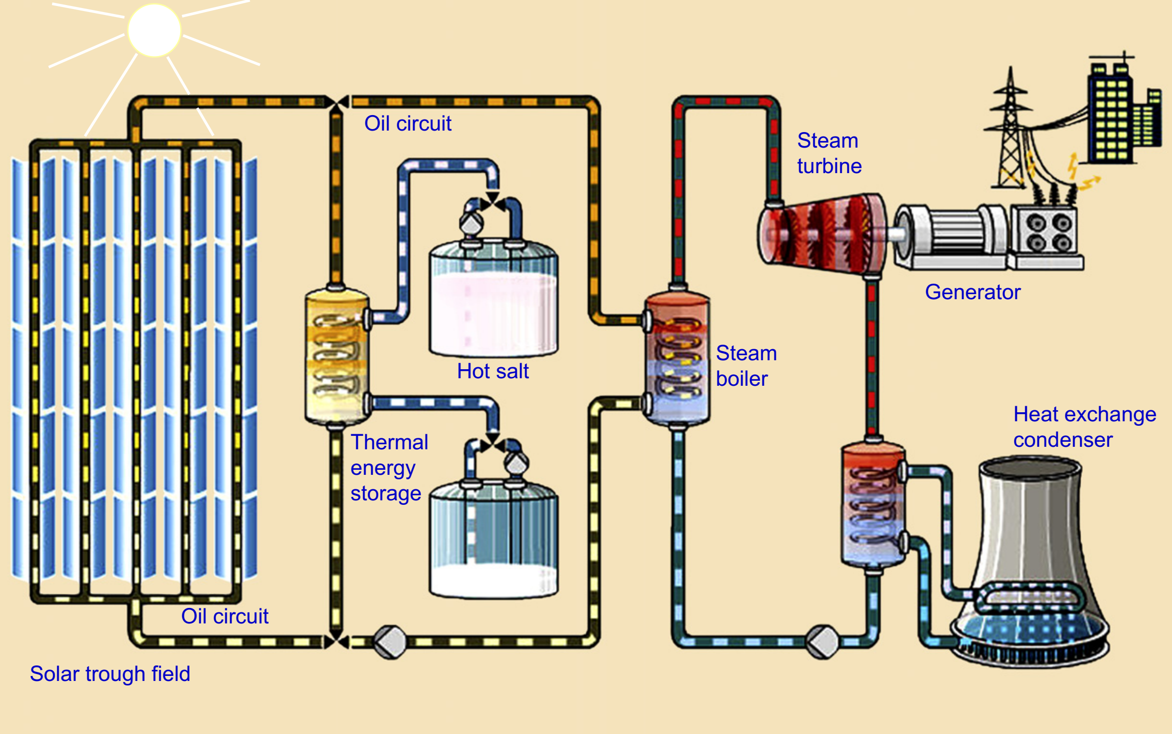


Figure 12 Schematic depiction of main components of a conventional parabolic-trough-CSP plant. Source: Wang, Y., 2008: *Parabolic Trough Power Plants (PTPP)*. [Available online at http://www.mtholyoke.edu/~wang30y/csp/PTPP.html.]

under development. Investment costs of €40–50 kWh^{-1} are foreseen for large scale storage systems.

3.11.6 CSP for the Cogeneration of Electricity and Desalinated Seawater

3.11.6.1 Basic Concepts

Figure 12 depicts the basic components of an operational CSP-parabolic-trough plant. A CSP plant also can be used to enable the desalination of seawater (DSW). Thus, such an integrated plant would enable the cogeneration of electrical power and desalinated seawater (called here a CSP–DSW plant). This addresses a number of particularly pressing problems in many countries, for example, Cyprus, including:

1. The generation of electricity by renewable sources rather than by the burning of fossil fuels
2. The resultant dependence on fossil fuel and international energy markets if energy is produced conventionally
3. The need for an environmentally friendly production of potable water through desalination

Thus, if realized, substantial benefits may be gained, despite the likely substantial capital investments needed to realize CSP–DSW plant.

The cogeneration of electrical power and desalinated seawater can be accomplished in two ways:

(a) By using the electricity that is being generated in a conventional desalination unit, either RO or MED (or any other desalination technology)
(b) By utilizing the remaining heat of the steam, after it has passed through the steam generator to produce electricity, as entry fluid for the first effect of a MED plant.

Whereas option (a) can be realized with any renewable power source (e.g., photovoltaics or wind), and option (b) is particularly – if not exclusively – suited for a CSP plant. Neither of the options has been realized in any operational plant at the present, even though currently operating CSP plants such as the ANDASOL 1 plant could readily accommodate a desalination unit according to option (a) (Trieb et al. 2009).

3.11.6.2 The CSP–DSW Project

The full integration of option (b) is less readily accomplished, but has been studied in detail by the Energy, Environment and Water Research Center (EEWRC) of The Cyprus Institute (2010). Figure 13 depicts schematically the main components of such a plant. The design envisioned incorporates a number of innovative elements/technologies, including:

1. Energy will be harvested by a field of heliostats on a hilly, south-facing location near the sea.
2. The solar energy will be captured by a central receiver and converted to heat and stored in a salt container of novel design at high temperatures.
3. Steam will be generated from the heat reservoir of the salt container or from an alternative thermal storage concept.
4. Electricity will be produced using a commercially available steam extraction turbine.

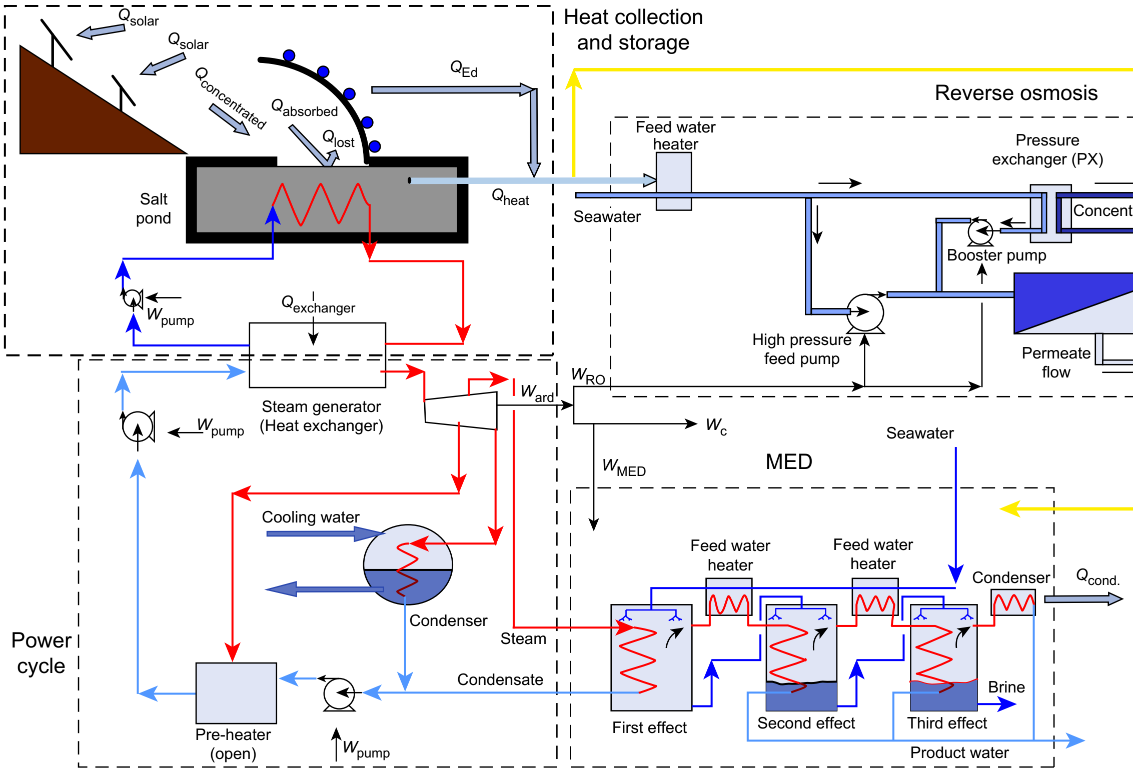

Heat collection and storage
Q_{solar}
Q_{solar}
$Q_{concentrated}$
$Q_{absorbed}$
Q_{lost}
Q_{Ed}
Q_{heat}
Salt pond
W_{pump}
$Q_{exchanger}$
Reverse osmosis
Feed water heater
Pressure exchanger (PX)
Seawater
Concentrate flow
Booster pump
High pressure feed pump
Permeate flow
W_{RO}
Steam generator (Heat exchanger)
W_{pump}
W_{ard}
W_c
W_{MED}
MED
Seawater
Cooling water
Condenser
Steam
Condensate
Power cycle
Pre-heater (open)
W_{pump}
Feed water heater
Feed water heater
Condenser
$Q_{cond.}$
First effect
Second effect
Third effect
Brine
Product water

Figure 13 CSP-DSW plant conceptual design with added RO modality. Source: The Cyprus Institute, 2010: *The CSP-DSW Project – An Overview, Nicosia, Cyprus*, 28 pp. [Available online at http://eewrc.cyi.ac.cy/system/files/CSP-DSW%20Stydy%20Overview.pdf.]

5. Desalinated water will be produced using an innovative multiple effect distillation (MED) facility with a thermal vapor compressor, from the heat output of the steam turbine and other heat sources of the system.
6. Alternatively or in addition, desalinated seawater may also be generated by an RO plant principally driven by electricity produced in the power cycle of the combined CSP–DSW plant.

It is obvious that the integration of all major components of this plant represents a tremendous integration/optimization task.

However, the Cyprus Institute study results in the conclusion that the concept of cogeneration of electricity and desalinated seawater using concentrated solar power is sound both from an engineering as well as from an economic and policy point of view. The heliostat–central receiver technology is judged to be the most suitable for a situation typical for a small- to medium-sized island such as Cyprus, wherein large flat areas are rather sparse. If implemented in conjunction with a substantial storage capability a 'base load' facility operating on a 24 h a day, 7 days a week schedule may be feasible. A detailed and sophisticated business model of a pilot plant whose conceptual design has been briefly described here reveals that such a plant, with a minimum electricity capacity of 4 MW_e and a (possibly) hybrid MED/RO desalination unit, will be economically feasible.

Currently, a number of detailed studies on key components, (such as the heliostats) as well as the receiver and storage units are currently undertaken at the EEWRC.

3.11.7 Conclusions

This chapter considers the links between water supply and renewable energies. While water scarcity represents a challenge to numerous regions of the world at present, climatic conditions could exacerbate this problem. In addition, groundwater resources in many parts of the world are increasingly threatened by overexploitation and/or contamination, implying significant risks to water security.

The provision of potable water in sufficient quantities and adequate quality in these regions is closely linked with energy needs, particularly, when seawater desalination is employed as a major source of drinking water. Renewable energies, notably solar energy, represent a viable alternative to conventional energy sources. This is particularly relevant for Northern Africa as well as countries of the eastern Mediterranean, as these regions combine significant water scarcity (cf. Figure 4) with copious quantities of solar irradiation (cf. Figure 3).

Novel technologies employing concentrating solar power for the cogeneration of electricity and desalinated seawater (CSP–DSW plants) have been addressed in recent studies (see, e.g., The Cyprus Institute 2010; Trieb et al. 2009). Such plants will have the advantage of addressing various particularly pressing problems in many countries, for example, Cyprus: (1) the generation of electricity by renewable sources rather than by the burning of fossil fuels, (2) the resultant dependence on fossil fuel and international energy markets if energy is produced conventionally, and (3) the need for environmentally friendly production of potable water through desalination. Thus, if realized, substantial benefits may be gained, despite the likely substantial capital investments needed to realize CSP–DSW plant. Although the overall technical and economical feasibility of a CSP–DSW plant has been demonstrated (The Cyprus Institute 2010), studies undertaken at present address a number of technical issues that need further clarification.

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3.12 Energy Buildings and Urban Environment

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Glossary

Air changes per hour (ACH) The fraction of a building's air volume, which is replaced each hour due to infiltration or ventilation use of outside air.

Anthropogenic Heat Sensible heat released to the environment as a result of energy use for human activities (aka waste heat). Examples of anthropogenic heat sources include automobile tailpipes, rooftop air conditioning equipment, and smokestacks associated with industrial processes.

Building envelope The outer shell of a building that separates the indoor and outdoor environments. This envelope consists of foundations, roofs, walls, doors, and windows.

Climate zone A geographical region (contiguous or otherwise) for which one representative set of climate characteristics can be defined for the purpose of building construction/insulation guidelines or standards. For example, the International Energy Conservation Code divides the world's climate into eight such zones.

Cooling and heating degree days Heating degree days (HDD) are calculated by subtracting the actual temperature from a base temperature (often 65 °F or 18 °C). This is done for each hour in a month or year and all nonnegative values are summed to obtain a total number of HDD. The premise is that additional heating is required for every hour when the temperature is below the base temperature and is proportional to the magnitude of this temperature difference. Cooling degree days (CDD) are calculated in the same way, but with the base temperature subtracted from the actual hourly temperature.

Design days In designing buildings it is generally desirable to size mechanical heating and cooling equipment so that they can meet comfort requirements for most days of the year. These sizing calculations are generally performed using a winter design day (typical very cold day) and a summer design day (typical very hot day). These design days do not represent absolute extreme conditions for the location under study. Rather, it is fully expected that there will be a small number of hours in any year when the building's heating and cooling equipment are not sufficient to maintain thermal comfort – for example, the building is slightly warmer or colder than desired.

Energy use intensity (EUI) The ratio of annual site energy use by a building to the floor area of that building. Sometimes EUI is applied just to electrical energy use. Other times it refers to the whole building energy use.

HVAC Energy use for Heating, Ventilation, and Air Conditioning (HVAC) is commonly lumped as a single quantity for analysis and discussion.

Operative temperature The equivalent temperature of an enclosure in which an occupant would experience the same heat gain or loss from radiation and convection as in the occupant's actual environment. This temperature takes into account not only ambient air temperatures and air velocity (for convection), but also the surface temperatures at which the walls, ceiling, and floor are radiating.

http://dx.doi.org/10.1016/B978-0-12-384703-4.00321-X

Peak Load Regional or local energy consumption generally peaks as a result of climate-dependent heating and cooling loads. Peak electric load in the summer is typically associated with high demand for air conditioning in the late afternoon hours. Peak electric load often dictates the generation capacity requirements.

Site/Source energy Site energy is the energy delivered to the building. The concept of source energy attempts to include the inefficiencies associated with power generation and transmission from power plants to the building. The site to source conversion factor used to account for these inefficiencies is typically between 2.5 and 3.5.

Typical meteorological year (TMY) A TMY is a representative description of the weather that a building might be expected to experience in a particular location, usually based on data from a local airport weather station. It is generally prescribed as a year's worth of hourly values for outdoor weather – temperature, humidity, wind speeds, solar radiation, etc. The TMY is distinct from the concept of a climate average in that it is generally comprised of actual data from the historical record, aggregated at the monthly level and smoothed. As such, it retains multiday weather events such as heat waves and droughts. For example, a TMY file for a particular site might include the weather from January of 2001, February of 2005, March of 1999, and so forth.

3.12.1 Introduction

Energy is central to the success of modern societies representing a fundamental resource, as well as a constraint for urban development. As cities grow, so too does the demand for energy and the various environmental consequences associated with energy production, transmission, and consumption. The global population continues to urbanize with the balance shifting from a primarily rural world to an urban one, just in the last 5 years. In larger industrialized nations such as the United States, upward of 75% of the population now lives and works in or near cities, and the average urban dweller spends on the order of 80% of their daily life in buildings. Buildings provide multiple functions in modern society. At a fundamental level, they provide shelter from the outdoor weather. This includes shelter from precipitation, winds, and undesirably hot or cold air temperatures. Buildings also provide the infrastructure for accomplishing work and entertainment. Electricity transmission lines and natural gas pipes supply the energy needed to power lighting, heating and cooling equipment, computers, televisions, and a myriad of office and household appliances. It therefore comes as no surprise that buildings represent the single largest consumer of energy in most developed nations. For example, in the United States it is estimated that buildings represent about 40% of all energy use with the remainder being roughly evenly split among the transportation and industry sectors. Of the sources of energy for end-use applications in buildings, electricity is the most versatile, and hence represents on the order of 70% of all energy use in buildings. Natural gas, fuel oil, and other types of heating fuels represent the remaining 30%.

In evaluating the relative energy efficiency of buildings, it is important to consider building use and climate. One useful metric of energy use in buildings is the Energy Use Intensity (EUI). The EUI is typically defined as the ratio of annual site energy use to building floor area. It can be used to refer just to the electricity use in a building – in which case it is usually defined in units of kBTU ft^{-2} or kWh m^{-2}. For example, the U.S. Department of Energy indicates that for new construction the EUI ranges from about 40 to 68 kBTU ft^{-2} (120–200 kWh m^{-2}) for large office buildings depending upon climate. The highest EUI values are associated with the coldest climates (e.g., Fairbanks, Alaska). The least energy intensive buildings are warehouses, and the most energy intensive buildings are generally restaurants and fast food establishments. Based on data from the Commercial Building Energy Consumption Survey (CBECS) across the United States, existing office building stock has an EUI in the range of 80–100 kBTU ft^{-2} (240–300 kWh m^{-2}), depending upon size category. In contrast, hospitals, restaurants, fast food, and supermarkets all have EUIs greater than 200 kBTU ft^{-2} (600 kWh m^{-2}).

The energy sector – and energy use in buildings, in particular – is inextricably linked with the urban climate system. Energy generation and consumption both affect and are affected by the urban climate in many complex ways. Perhaps the best known connection between energy and climate is the relationship between fossil fuel combustion in power plants and the release of carbon dioxide into the atmosphere. This emission of CO_2 is one of the major drivers of anthropogenic changes in climate statistics at the global scale (NRC 2005). Of course, fossil fuel combustion results in many other atmospheric emissions that contribute to both global and local environmental challenges. These emissions include particulate matter, such as fly ash and secondary sulfates and nitrates from coal-fired plants. The size distribution and chemical composition of particulate emissions from power plants determine their relative impacts on human health. Other emissions from fossil fuel plants include heat, water vapor, carbon monoxide, non-methane organic compounds, mercury, and various radioactive trace elements (particularly from coal combustion). These emissions have atmospheric residence times that range from minutes or days (e.g., water vapor) to tens or hundreds of years (e.g., CO_2). As a result, there are both local and global ramifications of power production. Thus, for some emissions from power plants, the relative proximity to population centers and the prevailing wind directions can be important factors in determining direct effects of power plant energy production on the urban atmospheric environment. While some types of power plants (e.g., hydroelectric, solar thermal, and nuclear) have relatively modest atmospheric emissions of chemical pollutants they still emit vast amounts of waste heat and require extensive cooling. Power plant efficiencies, in general, are bounded by Carnot cycle performance constraints, which dictate that the thermal efficiency of a device operating in a cycle between two temperature extremes, T_h and T_c is given by

$$\eta_{\text{th}} \leq 1 - \frac{T_c}{T_h} \qquad [1]$$

Thus, as a result of typical ranges of T_c and T_h available for practical power plant operation ($T_c \sim 300$ K and $T_h \sim 500$–800 K), most power plants operate at thermal efficiencies in the range of 40–60%. Other system inefficiencies such as inability to fully extract chemical energy from the power plant's fuel source further reduce the total power plant efficiency to a typical range of 30–40%. Depending upon the power plant, the waste heat is transferred to the atmospheric environment through evaporation of water in cooling towers, or to a large body of water in the form of a sensible increase in the temperature of the water leaving the cooling system. There are further losses in the transmission of power from power plants to the end users. These losses can be on the order of 0.25–1.0% per km. Thus, there is pressure to locate power plants near major urban centers and industrial consumers. As of 2007, the system-wide transmission and distribution losses in the U.S. electric grid were estimated at 6.5% (EIA 2011).

For every kilowatt hour of electricity delivered to an end user – say to power a desktop computer in an office during a workday – on the order of 2.5–3.0 kWh of fuel energy was expended at the power plant. Even so, that last kWh of energy follows the First Law of Thermodynamics – it is conserved. In the case of the vast majority of energy use in buildings, this conservation takes place in the conversion of energy to low grade waste heat. So, that 1 kWh used to power an office computer ultimately finds its way into the urban atmospheric environment, first by heating up the air in the office and then by being extracted by the building ventilation system.

As will be elaborated on in the following section, energy consumption consists of both a base load component and a weather-sensitive component. There are multiple factors affecting each component and finding levers to manipulate end-use energy consumption has been an ongoing challenge since the oil crisis of the 1970s. Base loads depend on technological innovation and human behavior, as well as their interactions. An interesting example of technological innovation at odds with human behavior is the evolution in refrigerator efficiencies that took place over several decades in the United States. In 1970, the average refrigerator used about 100 kWh year^{-1} of energy for each cubic foot of capacity. By the year 2000, through implementation of various standards – largely driven by California Energy Commission efforts – this average was reduced by more than a factor of three to about 30 kWh year^{-1} for each cubic foot of capacity. This was a great triumph on the technology side, driven by regulation. At the same time, however, technological progress led to a significant reduction in unit costs for refrigerators, from $1000 in 1970 to less than $500 in 2000. As a result, average refrigerator capacity increased by about 20% during this same period. Also, while it was quite uncommon in the 1970s for a household to have more than one refrigerator, it is much more common in modern U.S. households (EIA 2005). So, the tremendous energy savings made possible by efficiency improvements were somewhat reduced by evolving social and economic factors.

The portion of building energy consumption that depends strongly on weather is referred to as the weather-sensitive load. This load consists of air conditioning in summer, and heating in winter. Clearly, the relative magnitudes of heating and cooling demand are a strong function of climate. In some climates there is very little demand for heating, while in others there is little demand for cooling. There is a third class of cities, which have a more balanced demand for heating and cooling. As a result, building codes and practices vary substantially as a function of geographical location. Of course, weather-sensitive loads also depend very much on human behavior. There are well-established relationships between air conditioning energy consumption and outside air temperature. Multiple researchers, for example, have published data suggesting that in many U.S. cities total summer electricity use increases by 3–5 % per degree centigrade increase in the outdoor air temperature (Akbari et al. 1999; Akbari and Konopacki 2005; Lu et al. 2009). This sensitivity has important implications as it relates to both regional scale climate and local urban heat island (UHI) intensification. There are also data, however, suggesting that air conditioning behavior evolves. For example, in 1995 only about 33% of single family homes in Portland Oregon – a relatively mild summer climate – had air conditioning systems (AHS 1997). This number has grown at a rapid pace in recent years, increasing to 44% in 2002, and an estimated 50% or higher currently. This compares with more than 90% of residences across the entire United States that have some form of air conditioning (AHS 2009). This evolution likely is a result of relative costs for air conditioning equipment as well as an influx of residents from climates where air conditioning is prevalent, and the notion of buying a house without an air conditioner seems strange. This example points out a potential vulnerability that might be found in certain climate regions. Namely, as the local climate warms there may be a nonlinear increase in energy use for air conditioning due to the combined factors of increased market saturation of air conditioning and the underlying sensitivity of air conditioning energy use to ambient air temperatures.

3.12.2 Components of Building Energy Consumption

Energy consumption in buildings is as diverse as the many types of buildings and the climates within which they reside. Nevertheless, the end uses for which energy is consumed in buildings can be organized into four categories: lighting, plug loads, HVAC loads, and miscellaneous equipment. Each of these categories, in turn, consists of subcomponents, the relative magnitude of which will vary across the population of buildings. Energy use in each category also varies seasonally and diurnally due to variations in both weather and occupancy. While the role of weather is explicitly discussed in Section 3.12.3 Factors Influencing Building Energy Use, it is important to consider occupancy prior to discussing the specific components of energy use. So, the subsections below provide an overview of occupancy, followed by detailed descriptions of energy use within each end-use category. The last two subsections then describe variations in these loads as a function of building type residential–commercial.

3.12.2.1 Occupancy

Buildings exist to provide occupants with shelter from the outdoor environment and to create conditions suitable for everyday activities. So, one would expect that energy use in buildings ought to scale to some extent with the occupant density. An office building, for example, that opens early in the morning and closes in the evening should have relatively little energy consumption during the night. In contrast, an apartment whose occupant works during the day should have relatively little energy consumption during the day. So, in analyzing energy use in buildings it is important first to gain an understanding of occupancy. Of course, the scaling of energy use with occupancy is far from linear and differs for each subcomponent of energy consumption described below. Consider for example increasing occupancy from one to two persons per office. The lighting requirements for the space may only increase a small amount if at all, whereas the ventilation requirements and energy use for computing equipment essentially doubles.

Occupancy is often described using a 'design' value and a schedule. The design value is an estimate of the total space per occupant when the building is fully occupied. In models which simulate energy consumption in buildings, this is often given in terms of floor space per person. Common values range from 15 to 20 m^2 per person for an office space to 2–4 m^2 per person for a conference room. In computer modeling of building performance, it is generally assumed that for a commercial building the occupancy has a workday schedule that peaks around 80–90% of capacity in the early morning and mid-afternoon hours, with distinctive ramps from-to zero occupancy in the early morning and evening hours, and a lunchtime reduction in occupancy to around 50% of capacity (c.f., Hirsch 2011). Occupancy in residential buildings is typically much lower than that for commercial buildings. For example, a single occupant apartment is typically larger than 40 m^2, and a detached home for a family of four is usually larger than 180 m^2 ($\sim$1900 ft^2) or 45 m^2 per person. Aside from the end-use energy consumed by each occupant while in the building, occupants themselves act as sources of heat and moisture through metabolism and respiration processes. In fact, the typical person has a daily caloric intake that results in an average metabolic heat release of about 75–100 W.

3.12.2.2 Lighting

Lighting is an essential need in modern buildings. It enables extension of indoor activities well beyond sunset and ensures security and safety around perimeters of buildings, as well as in interior spaces such as stairwells. It is therefore a significant component of the total energy consumption in a building, often comprising 20–30% of total building energy consumption. Lighting needs are generally reported in terms of power per unit area ($W\,m^{-2}$), and lighting levels differ depending upon the intended use of a space. For example, typical lighting power for offices, hallways, and conference rooms is 14, 6, and 17 $W\,m^{-2}$, respectively. As with occupancy, these are the values assumed for full occupancy. With the exception of emergency and safety lighting, the actual lighting level in a building varies over the course of a day. It may peak around 90% of installed capacity and is generally no more than 5% of these peak values at night or on nonworking days.

The role of lighting in energy use and climate is twofold. First, the electricity used to power lights has its origin at a power station. So, there are waste heat and pollution emissions at the power plant, as well as losses in the transmission of this electrical energy to the building. Depending upon the technology used for lighting – for example, incandescent, fluorescent, compact fluorescent (CFL), or light emitting diode (LED) – the conversion of electrical energy to light will result in a certain amount of local waste heat at the point of use. As a general rule, to obtain the same level of lighting, incandescent lighting requires three to four times the power of CFL and five to six times the power of LED technology. Any energy used by lighting fixtures that does not generate visible light results in heat at the light bulb or fixture. It is important to note also that much of the light energy eventually gets converted to heat. Specifically, as light illuminates an interior wall it is partially absorbed and partially reflected. So, any light that does not escape through windows is also converted to heat in the building. This is why replacing inefficient incandescent bulbs with LEDs will reduce air conditioning loads in summer, but will also increase heating loads in winter. The same is true for other end-use efficiency measures related to plug loads and miscellaneous equipment.

3.12.2.3 Plug Loads and Miscellaneous Equipment

Plug loads consist of any electrical appliance that is plugged into an outlet. This includes items such as desktop computers, televisions, radios, and space heaters. Plug loads vary quite a bit depending not only upon building design, but also on occupant schedules and personal energy behavior. Thus, it is not uncommon for initial estimates of plug loads in a building to be off by ±25%. Underestimation of plug loads tends to be more common. This contributes to underestimates of air conditioning energy use and overestimates of heating energy use. As a general rule, plug loads are in the range of 10–20 $W\,m^{-2}$ for offices. Plug loads are generally closely tied to occupancy. Of course, many devices continue to draw power even when they appear to be turned off. These loads are generally referred to as phantom loads, but are usually only a few tenths of a watt to several watts per device.

3.12.2.4 HVAC Loads Including Environmental Loads

Most modern buildings require some level of heating, cooling, and mechanical ventilation. The heating and cooling demand is generally driven by the goal of maintaining the occupied space within a comfortable temperature and humidity range. The most widely promoted guidance for thermal comfort comes from the American Society for Heating, Refrigeration and Air Conditioning Engineers (ASHRAE) in the form of the ASHRAE 55 standard for Thermal Environmental Conditions for Human Occupancy (ANSI/ASHRAE 2010). The acceptable range of thermal comfort depends upon temperature and humidity, but also factors in seasonal and clothing considerations.

The extent to which indoor ambient conditions deviate from the comfort region in Figure 1 results in the demand for heating, cooling, or dehumidification. The vertical axis in this figure is the

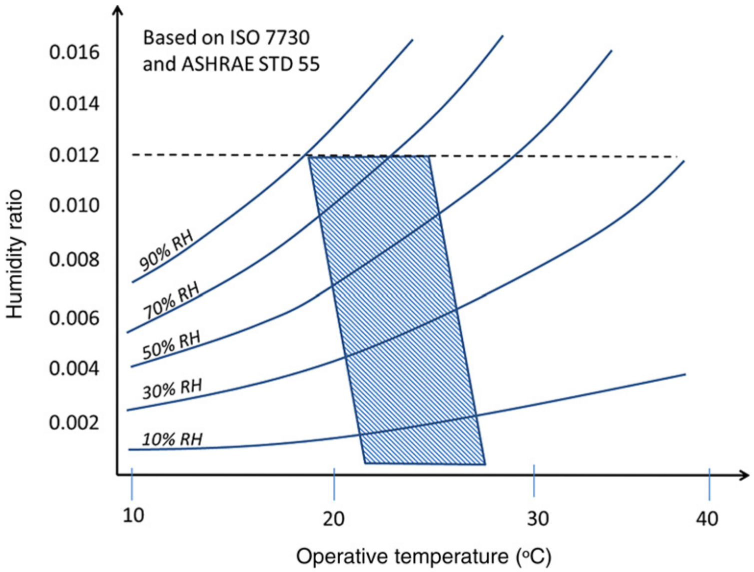

Figure 1 Thermal comfort diagram (after ASHRAE 55 standard). Shaded region represents temperature and humidity range within which typical building occupants are comfortable. Actual location and size of this region shifts as a function of clothing level and individual preferences. Reproduced from ANSI/ASHRAE, 2010: *Standard 55-2010–Thermal Environmental Conditions for Human Occupancy* (ANSI approved). ASHRAE, 40.

nondimensional humidity ratio – mass of moisture in a unit volume of air divided by the mass of the dry air volume. The horizontal axis is the operative temperature which is a measure of the effective temperature that a person is exposed to – accounting for sensible air temperature, as well as radiant and convective exchange with the surroundings. The shaded region in this figure represents a region of conditions within which a typical person would feel comfortable. This figure illustrates the importance of both temperature and humidity in affecting thermal comfort. Often, the cooling equipment in a building act as the mechanism for dehumidification – for example, residences in the southern United States often run their air conditioners throughout the night during hot and humid summer months in order to remove moisture from the indoor air, even though the air temperature might otherwise be comfortable.

In the absence of mechanical HVAC systems indoor conditions will vary in response to multiple factors. First, internal loads (plug and lighting loads and various electric and gas powered appliances) within the building necessarily result in waste heat. This waste heat warms the indoor air and the interior surface temperatures. As a general rule of thumb, every joules of energy consumed within the building results in a joule of waste heat within the building. The exceptions include the direct loss of lighting power through windows and the removal of heated water through sewer pipes. As a direct function of human (and pet) metabolism, occupants within a building are another source of heat. As noted earlier, this metabolic heat loss varies from individual to individual and as a function of activities, but in general, each human occupant represents an additional 75–100 W of heating. These internal loads associated with energy use and occupancy, however, are sometimes exceeded by external loads associated with the outdoor environment.

Solar radiation is one of the most significant external loads on a building, particularly in the summer season. Depending upon latitude the peak solar radiant flux incident on a building may be as high as $1100\,\mathrm{W\,m^{-2}}$ in summer. This short-wave radiative load on the building penetrates the building envelope through two pathways. Some of the radiation passes directly through the windows. Depending upon the construction details of the windows (e.g., number and thickness of panes of glass, presence of coatings, air gap between panes and frame characteristics) the amount of solar radiation making it through each window may vary from as little as 0.25 for a good double pane window with a reflective coating to as much as 0.85 for a single glazed window. Windows are typically the largest driver of environmental heat gain in buildings. This is due both to the relative transmissivity of windows to solar radiation and the generally high window to wall surface area ratios (windows are generally 30–50% of the wall surface area).

Solar radiation combines with convection to influence the total heat conduction through the opaque surfaces of the building envelope. While this component of environmental load on buildings is typically less significant than the direct solar gain through windows, it can be important depending upon the level of building insulation and the quality and relative surface area of windows.

A final element of environmental loads that is sometimes overlooked is heat and moisture transport across the envelope directly through air exchange. While some level of outdoor air exchange is highly desirable to maintain good air quality, air leakage across the building envelope is generally greater than needed to maintain good air quality. This is particularly true in residential structures where a typical infiltration rate might be on the order of 1–3 air changes per hour (ACH). In the best sealed envelopes the infiltration ACH can still be greater than 0.2. All of this unintentional air exchange between the indoor and outdoor environments leads to movement of heat and moisture across the building envelope.

There is a wide variety of systems in use for heating, cooling, and ventilating buildings. Boilers, furnaces, and electric resistance heaters are typically used to add heat to buildings while cooling is typically accomplished via packaged 'DX' (Direct Expansion) air conditioning units, heat pumps, or cooling towers. Boilers, furnaces, and electrical resistance heaters generally have very high conversion rates – for example, 1.0 J of energy delivered to the building (e.g., via natural gas line or electricity) for heating is converted into very nearly 1.0 J of heat within the building. Some losses exit the building via stacks or chimneys. Ultimately if a building is operating in a nominally steady mode, then all heat added to the building to maintain comfort must be balanced by an equal amount of heat escaping into the urban environment. So, if one knows the quantity of energy used for heating that can be equated directly to anthropogenic waste heat.

Air conditioning is a different story. Different metrics of efficiency apply to the differing types of equipment in use for air conditioning. For example, air conditioning equipment that operates on a refrigeration cycle is generally evaluated based on its Seasonal Energy Efficiency Ratings (SEER) or Coefficient of Performance for a refrigeration cycle ($\mathrm{COP_R}$), where by definition $\mathrm{SEER} = 3.412 * \mathrm{COP_R}$. The coefficient of performance simply measures the desired output of the AC system – the removal of a quantity of heat Q_L from the 'low' or cool side of the cycle (the building) relative to the net amount of work required to accomplish this heat removal process ($W_{\mathrm{net,in}}$):

$$\mathrm{COP_R} = \frac{Q_L}{W_{\mathrm{net,in}}} \qquad [2]$$

But the First Law of Thermodynamics requires that the refrigeration cycle exhausts heat (Q_H) on the hot side of the cycle (the outdoor environment) with the resulting energy balance:

$$Q_H = Q_L + W_{\mathrm{net,in}} \qquad [3]$$

Combining these expressions,

$$Q_H = W_{\mathrm{net,in}}(1 + \mathrm{COP}) \qquad [4]$$

Thus, the amount of heat exhausted into the outdoor environment (Q_H) by a traditional refrigeration cycle-based air conditioning system will be larger than the amount of heat removed from the building. In fact, $\mathrm{COP_R}$ values generally range from about 2 for older systems to more than 4 for some of the newer technologies. This means that for every joule of energy used to cool a building ($W_{\mathrm{net,in}} = 1\,\mathrm{J}$) the waste heat removed from a building ($Q_H = 3\text{–}5\,\mathrm{J}$). So, in estimating the anthropogenic waste heat associated with DX-style air conditioners it is important to note that the waste heat is at least three times the magnitude of the energy used for air conditioning. There is an entire class of air conditioning systems, however, for which this analysis is not applicable. Specifically, evaporative–cooling systems, common on larger commercial buildings and also on residential buildings (as 'swamp coolers') in some climates, remove the heat load from the building through a combination of evaporative (latent) and convective (sensible) heat exchange. The actual fraction of building load which is removed in the form of latent heat depends on atmospheric conditions, supply water temperatures, and system operating conditions. So, while it is difficult to predict what fraction of cooling tower waste heat emissions are in the form of latent heat-sensible, such systems often operate with more than half of the waste heat being latent. So, again, energy used to run such systems is not indicative of the amount of sensible waste heat emitted into the urban environment.

So, in summary, there are many factors that contribute to the demand for heating and cooling in a building. Ultimately, the total waste heat emitted from a building is a combination of the heat associated directly with energy use within the building and with the environmental load that would generate energy demand for heating and cooling even in the absence of any energy consumption for other purposes in the building. These factors contributing to waste heat emissions from buildings are summarized in Figure 2.

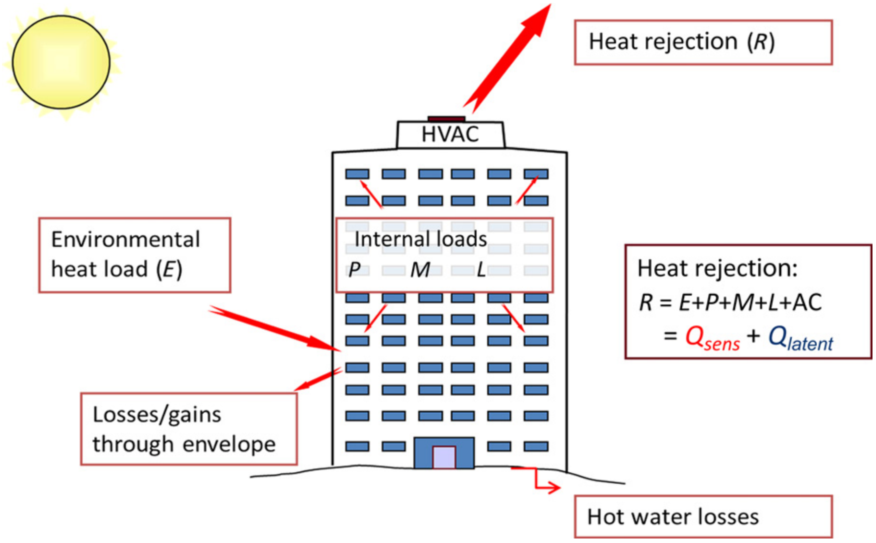

Figure 2 Summary of loads affecting the energy consumption and waste heat emissions from a building. The total heat rejection to the environment is a combination of sensible and latent heat depending upon the type of cooling equipment employed. In summer the environmental loads may be the same order of magnitude as the building energy consumption.

3.12.2.5 Residential Buildings

Residential buildings are broadly classified into multifamily residential (MFR) and single family residential (SFR). These correspond to apartments–condominiums and detached houses. The relative proportion of housing in either of these categories varies widely. In the United States roughly 75% of households are SFR. There can be sharp contrasts from one city-state to another, however. For example, only 51% of the households in the State of New York are SFR. In Midwestern states such as Iowa this fraction increases to 82%.

Variation of energy use across building types can be viewed using two different metrics: energy use per capita and energy use per unit floor area. Densification of the urban population into MFR housing results in a decrease in energy use per capita due to sharing of common energy sources for lighting and HVAC. On the other hand, MFR housing results in an intensification of energy use per unit floor space. Thus, to the extent that MFR housing results in denser populations in cities it also increases the density of energy use and waste heat emissions within the city.

One important characteristic of residential housing is its diurnal and seasonal profiles of energy consumption – and thus waste heat emissions. The typical household is characterized by high levels of activity during the morning and evening hours, with a general reduction in energy use during working hours. The energy consumed for HVAC follows the activity patterns with residential air conditioning driving much of the late summer afternoon (3–5 p.m. local time) peak in many utility load curves. Likewise, the requirement to maintain thermal comfort during cold winter nights results in high levels of heating fuel use throughout winter nights, even though other components of energy use are small.

3.12.2.6 Commercial Buildings

The U.S. Department of Energy's CBECS (EIA 2003) classifies commercial buildings into 14 principal activity categories. The five most prevalent building types (based on total floor space) are: (1) office, (2) mercantile, (3) warehouse storage, (4) education, and (5) lodging. Ranking the same 14 principal activity categories by total primary energy consumption, the five most energy intensive types are: (1) office, (2) education, (3) health care, (4) lodging, and (5) warehouse storage. So, clearly, office buildings are particularly important contributors to the overall building energy consumption in the United States and most industrialized countries. In fact, office buildings in the United States consume 38% more energy than the next most energy intensive building category – education.

In contrast to residential buildings, commercial buildings have energy consumption profiles that are driven largely by the defined work week. That is, most commercial office buildings have very low occupancies on weekends, holidays, and before 7 a.m. and after 6 p.m. local time on a weekday.

Most commercial office buildings are managed in such a way to reduce energy consumption when workers are largely absent. To accomplish this, the ventilation schedule is generally reduced during nonworking hours and the setpoint temperature for thermal control (heating or cooling) is relaxed so that the building's thermal environment is allowed to 'float' at night and on nonwork days. Due to the lag between programmed setpoints and realized thermal comfort in buildings, most commercial office buildings are 'turned on' an hour or so before the first wave of occupants arrive each workday.

3.12.3 Factors Influencing Building Energy Use

Having described the individual components of energy use in buildings, and the roles of occupancy and building class we can now consider the main drivers that influence building energy use with a particular emphasis on the role of climate and weather.

3.12.3.1 Climate and Weather

This section introduces aspects of the urban climate system including regional climate, UHI, and global environmental change with respect to their consequences for energy use in buildings and the associated feedback of waste heat emissions. It answers questions such as: what is the climate-sensitivity of building energy use? It also introduces the concept of positive and negative feedbacks in the system (e.g., global/local warming increases demand for air conditioning in summer and increased AC use results in additional waste heat that further warms urban areas).

The primary connection between outdoor atmospheric conditions and energy use in buildings is the role that ambient temperature plays in affecting heating and cooling loads. A generalized depiction of this relationship for power utilities in hypothetical cities is illustrated in Figure 3. Representative curves are presented for winter peaking (cold climate) and summer peaking (warm climate) utilities. The cooling and heating load sensitivities, S_{CL} and S_{HL}, respectively, indicate the

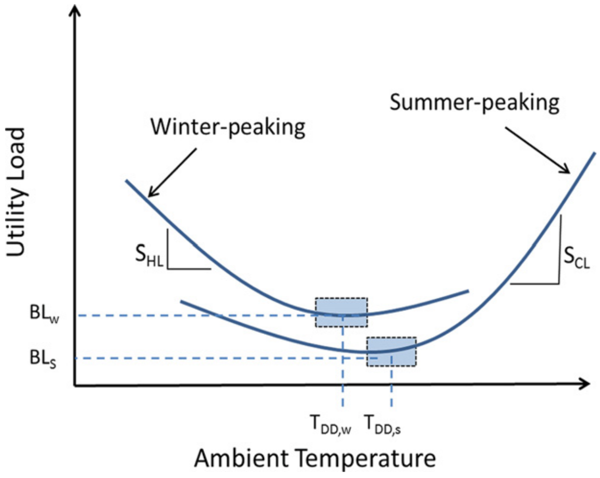

Figure 3 Energy consumption profile as a function of outdoor ambient air temperature. Curves are shown for winter and summer-peaking (cold and warm climate) utilities. Base loads (BL), threshold (T_{DD}) temperatures, and heating and cooling load sensitivities (S_{HL} and S_{CL}) are shown. Shaded regions indicate temperature ranges over which load is minimally sensitive to changes in ambient temperatures.

rate at which energy consumption increases with air temperature in summer or decreases with temperature in winter. The U-shape of these curves demonstrates the reversed role that ambient air temperature has in winter vs. summer. It also reveals that during shoulder seasons (e.g., Fall and Spring) building energy consumption reaches a minimum value, which can be thought of as the weather-independent base-load (BL). The shaded regions indicate temperature ranges over which utility loads are relatively insensitive to changes in ambient temperature. These regions are centered on nominal threshold temperatures for the winter and summer peaking utilities, $T_{\mathrm{DD,w}}$ and $T_{\mathrm{DD,s}}$, respectively.

To simplify the relationship between ambient temperature and utility system or individual building energy loads, energy analysts have long used two parameters that characterize the ambient temperatures in a city as they relate to demand for heating and cooling of buildings. These metrics are heating and cooling degree days (HDD and CDD, respectively). They are defined in such a way as to account for the fact that heating demand in most cities approaches zero for ambient air temperatures above some threshold (T_{HDD}) and cooling demand approaches zero for ambient air temperatures below a cooling threshold (T_{CDD}).

$$\mathrm{CDD} = \sum \frac{1}{2}[(T - T_{\mathrm{CDD}}) + |(T - T_{\mathrm{CDD}})|] \qquad [5]$$

$$\mathrm{HDD} = \sum \frac{1}{2}[(T_{\mathrm{HDD}} - T) + |(T_{\mathrm{HDD}} - T)|] \qquad [6]$$

The first and second terms on the right side of each of these equations only differ by the use of absolute values for the second terms. Thus, the form of these expressions results in no increment to the degree day calculation for periods during which the ambient temperature is either warmer or colder than the HDD or CDD threshold temperatures, respectively. These expressions should be evaluated using hourly temperature data, although in many instances daily mean temperature data are used. The actual values of the threshold temperatures vary from city to city, in part due to acclimatization of populations to warm or cool temperatures, and in part due to differences in building characteristics. Furthermore, the heating and cooling thresholds within any particular city may differ from each other, resulting in a temperature regime (between T_{HDD} and T_{CDD}) with relatively little demand for heating or cooling (the shaded boxes in **Figure 3**). For the sake of simplicity, most heating and cooling analyses in the United States use a common cooling and heating threshold temperature of $T_{\mathrm{DD}} = 65\ ^\circ\mathrm{F}$ (18 °C). It is important to note, however, that this is not an international standard. For example, in China it is common to use 26 °C as the threshold temperature for cooling (Zhang et al. 2002). It is therefore challenging to compare degree days from one country to another unless the raw temperature data from reliable weather stations are reanalyzed using a common base temperature. **Table 1** presents representative degree day data for a number of U.S. cities, using 65 °F as a threshold for both HDD and CDD. With CDD and HDD as metrics for evaluating the weather-sensitive component of energy consumption in buildings it thus becomes easier to compare buildings in differing climate regions. In the absence of significant differences in building infrastructure and human behavior one would expect energy consumption for heating and cooling to scale with degree days (Scott et al. 1994; Sailor and Munoz 1997).

Table 1 Normal annual heating and cooling degree days (65 °F base) for U.S. cities for the period 1961–91 (from NOAA 2008). These data are commonly presented in units of °F days. To convert to °C days (with 18 °C base) these values must be divided by 1.8

City	*Annual heating degree days (base 65 °F)*	*Annual cooling degree days (base 65 °F)*
Atlanta, GA	2827	1810
Chicago, IL	6493	835
Denver, CO	6128	695
Houston, TX	1525	2893
Los Angeles (Airport), CA	1286	682
Miami, FL	155	4383
New York (Central Park), NY	4744	1160
Phoenix, AZ	1040	4355
Sacramento, CA	2666	1248
Seattle (Airport), WA	4675	173

Reproduced from NOAA, 2008: Climatography of the United States, No 81, Supplement No. 2: Annual Degree Days to Selected Bases 1971–2000. [Available online at http://cdo.ncdc.noaa.gov/cgi-bin/climatenormals.]

It is important to recognize, however, that interactions between the energy sector and climate extend far beyond the simple temperature-dependence of demand just discussed. One of the most telling stories of energy sector vulnerability to multiple environmental stressors is that of the March 2011 earthquake and resulting Tsunami that hit the eastern coast of Japan. The devastation caused by the flooding forced the shutdown of the Fukushima Daiichi nuclear power plant which had an installed capacity of 4696 MW and provided an annual electric power generation of nearly 30 000 GW-h for the region. The shortfall in generation capacity resulted in 3-h rolling blackouts throughout Japan, starting directly in the aftermath of the disaster. The energy-related ramifications of this disaster were further exacerbated by the increasing electricity demand as the weather warmed into the summer months. Fortunately, in efforts to avoid more drastic blackouts during the hot summer months, Japan was able to use demand management strategies to reduce peak demand for 2011 by 18% relative to the summer of 2010. This incident demonstrates not only the important interacting roles of multiple coincident environmental stressors acting in concert, but also the resiliency inherent in the system via social and economic drivers.

Long-term climate variability and change will affect the energy sector in many complex ways beyond the simple weather-sensitivity of HVAC loads. For example, changes in frequency and magnitude of precipitation events combined with a warmer climate will likely strain water resources, which are linked to energy resources. For example, fossil fuel and nuclear power plants require large amounts of cooling water. Furthermore, environmental restrictions limit the amount of heat such plants can release into lakes and rivers, and such restrictions are likely to be more challenging, as these thermal reservoirs heat up due to any changes in climate statistics. Also, hydroelectric and biofuel-based power generation is tightly coupled to the hydrologic cycle and in competition with other demands for fresh water supplies (agriculture, drinking water, recreation).

3.12.3.2 Construction Characteristics, Behavior, and Management Practices

There are many complex relationships affecting energy consumption by buildings and their occupants. The role of human behavior is complicated, as it is influenced by building construction characteristics and interacts with large-scale social norms, and management practices. Thus, these interrelated factors are discussed together in this section.

Infrastructure plays a significant role in affecting energy use in buildings. Two buildings in the same climate with similar occupants and functions can have vastly different energy use resulting from differences in construction quality, insulation levels, glazing-to-wall surface area ratios and equipment efficiencies. Building-to-building variations within a city are largely driven by variations in building vintage, which in turn reflects the differing building codes in force at the time of construction, as well as relative improvements in efficiencies of building equipment. For example, many U.S. states implement building code upgrades periodically that mirror, but lag, updates in national standards (e.g., ASHRAE 2007) or international model codes (ICC 2009). Variations from one city to another or from one country to another reflect the relative energy efficiency sophistication of building codes and management practices within the building industries. These differences are further influenced by differing social attitudes, economic priorities, and the relative severity of summer and winter weather conditions.

While there is a rich history of data and analyses of building stock characteristics, energy consumption, and energy standards in western countries (Scott et al. 1994; Huang and Brodrick 2000; EIA 2005; Bruhns and Wyatt 2011; Theodoridou et al. 2011) much of the current and future growth is in regions of the world with relatively nascent building energy efficiency efforts. Focusing on energy consumption within the residential and commercial building sectors, data from the International Energy Agency (IEA 2011) show a wide range of annual energy use per capita with Canada and the United States having among the most energy-intensive building sectors (81.4 and 65.4 GJ per capita, respectively). Europe tends to have lower consumption rates, with Germany, the United Kingdom, and Sweden consuming 49.7, 39.8, and 48.7 GJ per capita in their building sectors, respectively. Japan has an even lower energy consumption rate of 37.1 GJ per capita in its residential and commercial buildings. While some of the differences in these energy use intensities result from climatic differences, much is due to the differences in social and economic factors.

Of course, the tremendous recent and forecasted growth in India and China brings to the forefront questions related to how those countries will develop and deploy more stringent building energy efficiency standards. While their building sectors currently only consume 6.6 and 12.4 GJ per annum per capita, it is likely that these energy use intensities will substantially increase in coming decades. A study in 2007 suggested that the Chinese government's own statistics on commercial building energy consumption underestimated commercial energy consumption by 44% (Bressand et al. 2007). Nevertheless, recent analyses conclude that commercial buildings in China are substantially less energy intensive than buildings in corresponding climate zones in the United States The explanation for this includes multiple related factors. First, commercial buildings in China generally provide a lower level of service related to maintaining thermal comfort. It is common, for example, for office buildings in China to use air conditioning only when the outdoor air temperatures are above 26 °C – a much higher cooling threshold (by about 8 °C) than in western countries. Furthermore, due to relatively lower labor costs, buildings in China may be more carefully managed than typical buildings in North America and Europe.

3.12.4 Adverse Effects of Energy Consumption in Buildings

Buildings play a crucial role in improving quality of life of occupants by isolating them from unpleasant outdoor conditions and providing safe environments for work, rest, and recreation. The energy used to provide these benefits in the indoor environment, however, ultimately affects the outdoor environment through waste heat and pollution emissions.

3.12.4.1 Buildings as a Key Determinant of Peak Utility Loads and Capacity Requirements

In developed countries, buildings are typically the dominant energy-consuming sector, and are by far the largest consumers of electricity in any city. As a result, buildings play a key role in dictating peak electricity loads, which in turn dictate the requirements for electric energy generation capacity (power plant MW). Energy consumption in buildings can be divided into two categories – base load for activities that are independent of ambient weather and weather-sensitive load for heating and cooling applications. While the base load has diurnal fluctuations that track human activity – peaks in the early morning and late afternoon – the weather-sensitive loads can introduce perturbations that are several times as large as the variations in the base load. This is particularly true in the summer for cooling-dominated climates where electricity loads associated with air conditioning demand in buildings define the timing and magnitude of peak consumption. As demand for electricity increases utilities are forced to ramp up reserve power plants. Under extreme conditions, the utility generation-transmission infrastructure may be incapable of meeting total demand, necessitating the implementation of demand management strategies to throttle back load. In such cases, the risk of electricity brownouts and blackouts increases. For example, an extreme heat wave in Western North America on 10 August 1996 buckled the Western Intertie resulting in power outages for millions of customers across nine Western States and portions of Mexico (NWPCC 2011). While extreme heat, winds, and other weather-related phenomena are significant direct contributors to power grid reliability issues, they often represent indirect causes or triggers for failure. For example, the great Northeast United States blackout of August 2003 was triggered by several failed transmission lines near Cleveland Ohio, which resulted in a cascade of system failures across Northeast United States and into Canada, affecting over 10 million people. The failure appears to have been precipitated by heavy demand on several transmission lines which caused them to overheat, sag, and come into contact with trees (US-CAN 2004). Similar large-scale blackouts in Brazil and Paraguay in November 2009, Italy in September 2003, and elsewhere have been attributed to wind, rain-snow events that triggered cascades of failures.

Building resiliency into the energy supply infrastructure is one of the grand challenges faced by modern society. Regional and international pressure to reduce reliance on fossil fuel based power plants is introducing renewable energy into the fuel mix at ever increasing levels. The climate-dependency and intermittency of such supplies and challenges associated with transmission and storage limitations is just now being felt by energy providers. For example, in Spring 2011 the Northwest United States had high levels of snow pack and associated runoff to be handled by its hydroelectric facilities that coincided with high wind resource. The transmission system could not handle the excess supply and as a result the Bonneville Power Administration (BPA) refused to purchase wind power from facilities in the region. The alternative would have been to allow hydroelectric capacity to flow unused over dam spillways, with the associated loss of free electric power, and potentially adverse effects on fish populations associated with the resulting increase in dissolved gas in their aquatic habitat. As wind power and solar power facilities become more prevalent, scenarios such as this will likely be repeated. While much of the solution to these challenges will come from improved transmission infrastructure and new energy storage technologies, there is no question that the building sector can be part of the solution through improved end-use efficiency and management strategies.

3.12.4.2 Waste Heat Emissions from Building Energy Use

If one considers a control volume drawn around a building it is possible to trace all flows of energy into and out of the building. As noted previously, energy interacts with a building in the forms of incident solar radiation, long-wave radiant exchange with the sky, and other surfaces; convection (and infiltration) of heat to/from outside air; and generation of waste heat associated with the use of electricity and end-use combustion processes within the building. While the building itself stores heat diurnally and seasonally, it is reasonable to consider the building as being in pseudo steady-state. That is, any energy crossing the building envelope must be rejected to the environment. While some of this rejected heat is in the form of waste heat entering the sewage stream, most of it is in the form of sensible and latent heat rejection to the urban atmosphere.

The magnitude of sensible waste heat emissions from a building varies across the seasons and depends upon the type of mechanical cooling it employs (Heiple and Sailor 2008). For a small office building with a sensible air-to-air heat exchange system the total sensible waste heat in summer can be much larger than the total building energy consumption – due to the need for the HVAC system to reject environmental loads in addition to rejecting loads associated with internal energy consumption. In contrast, if the building is cooled through use of evaporative–cooling towers, then much of this heat load is rejected from the building in the form of latent heat. The magnitude of this waste heat emission depends upon the environmental factors noted above, as well as building construction details, building equipment, and characteristics of energy use within the building. According to the U.S. Department of Energy the average annual energy consumption across all commercial building types in the United States is roughly 90 kBTU ft^{-2} ($\sim$280 kWh m^{-2}). To put this in context, consider the solar radiation incident on a city over a year. Data from NREL indicate that the solar insolation ranges from about 3.0 to 6.0 kWh m^{-2} per day for most mid-latitude cities (NREL 2011). On an annual basis this corresponds to about 1000–2000 kWh m^{-2}. So, a typical six-story commercial building in the United States consumes an amount of energy (electrical and natural gas) that is comparable in magnitude to the total solar radiation incident on the building site. This is precisely why the goal of developing net-zero energy consumption buildings is so challenging. With the highest efficiency photovoltaic systems only on the order of 20% efficient any realistic net-zero energy project for a multi-story building must meet the net-zero goal by a combination of reducing EUI, employing efficient energy exchange-storage strategies such as geothermal wells, as well as extensive deployment of photovoltaic power generation on site.

There is no doubt that buildings are responsible for sizable emissions of heat and moisture. The important question, however, is how do these emissions affect the urban climate system. Qualitatively it is apparent that such emissions should increase the magnitude of the UHI and increase humidity levels. But how these increases in temperature and humidity affect quality of life for the urban resident depends on multiple factors. First, there is a clear differentiation between the implications of these emissions in summer vs. winter. Whereas added heat in summer may not be desirable in many mid- and low-latitude cities, it may actually be beneficial in winter, particularly in mid- and high-latitude cities.

While actual quantification of anthropogenic heat release from buildings, vehicles, and industry remains an uncertain science, many studies have explored the effects of anthropogenic heat emissions on the urban climate of cities (see Sailor 2011 for a review of such studies). For example, a study by Torrance and Shum (1975) used inventory estimates of annual energy consumption to estimate waste heat associated with energy consumption in a city. They found this heating to be as large as 135 W m^{-2} and used a simplified transient one-dimensional atmospheric model to assess its atmospheric consequences. They found that this level of anthropogenic heating could result in up to a 4 °C warming of near-surface air temperatures in summer. In a study involving a more sophisticated representation of anthropogenic heating in Tokyo, Kimura and Takahashi (1991) used detailed land use and energy consumption data to estimate anthropogenic heating and its impact on urban air temperatures. Peak anthropogenic heating from that analysis was on the order of 100 W m^{-2}. Using these sensible heat emissions as a source term in a three-dimensional atmospheric model they then found that much of the nocturnal summertime heat island in Tokyo (2–3 °C) is due to anthropogenic heating.

Ichinose et al. (1999) used energy statistics for various building types and end uses in Tokyo and detailed digital land use data to estimate hourly anthropogenic heating on a much finer grid resolution of 25 m by 25 m. As is to be expected, the high spatial resolution led to some rather large estimates of heating associated with grids that were centered on large high rise office buildings. Recall, that the energy use in a typical six-story commercial building can rival the sun's energy input averaged over the footprint of the building. Ichinose found that hourly energy consumption at this fine scale (assumed equal to anthropogenic sensible heating) could be as large as $1590\,\mathrm{W\,m^{-2}}$ in the winter and was more than $400\,\mathrm{W\,m^{-2}}$ during summer daytime hours. His analysis also integrated these estimates of anthropogenic heat into a regional atmospheric model simulation. The result was a summertime air temperature elevation of about 1 °C during the day, and as much as 1.5 °C at night. In winter, when the magnitude of anthropogenic heating was much higher the nocturnal warming reached 2–3 °C.

Fan and Sailor (2005) implemented city-scale estimates of anthropogenic heat emissions for Philadelphia, Pennsylvania (obtained from Sailor and Lu 2004) into a mesoscale atmospheric model. That study found peak anthropogenic heating at the city scale to be $60\,\mathrm{W\,m^{-2}}$ in summer and approximately $90\ \mathrm{W\ m^{-2}}$ in winter. The impacts of this anthropogenic heating on urban air temperatures ranged from 1 °C in summer to 3 °C in winter.

Thus, in aggregate, these studies suggest that anthropogenic heating in cities can be on the order of $100\text{–}1000\ \mathrm{W\ m^{-2}}$, easily rivaling the energy input from the sun. Furthermore, this level of waste heat emission into the urban atmosphere can raise local air temperatures by 1–3 °C depending upon time of day and season. Clearly, one limitation of this prior work is the reliance on crude inventory-based estimates of anthropogenic heating that assumes energy consumption is equal to anthropogenic sensible heat release. Also, modeling of anthropogenic heat effects on the urban atmosphere is generally accomplished using regional scale atmospheric models that do not resolve buildings or the urban canopy within, which the emissions are assumed to mix (and some emissions occur at significant elevation from rooftop HVAC equipment on tall buildings). A third limitation is the general inability to obtain observational validation of the results of the modeling studies. Nonetheless, it is reasonable to conclude that waste heat emissions associated with energy use in buildings can have a significant effect on urban air temperatures.

3.12.4.3 Air Quality Implications of Urban Energy Use

Energy use in buildings affects both indoor and outdoor air quality. While much of the focus when it comes to urban air quality is in the outdoor environment, it must be noted that typical urban residents spend more than 75% of their time indoors (e.g., 8 h sleeping, 8 h working, and 2 or more hours of other indoor activities such as eating). So, from an exposure standpoint, the indoor air quality is at least as important as the outdoor air quality.

The primary air quality concerns indoors are associated with elevation of CO_2 levels, mold spores, volatile organic compounds (VOCs), and CO associated with indoor combustion sources. In efforts to reduce exposure to indoor air pollutants various building design and ventilation standards have been developed over the years. Chief among these is ASHRAE 62.1, which dictates a nominal ventilation rate of 15 CFM (cubic feet per minute) or $0.44\ \mathrm{m^3}$ per minute for each building occupant (ASHRAE 2010). The implication of such ventilation standards is that indoor air must be continuously replaced with 'fresh' outdoor air. While some buildings may meet this requirement passively through infiltration, most classes of commercial buildings meet this standard through mechanical ventilation, which also requires additional energy consumption for conditioning of the outside air. Such ventilation results in the exchange of indoor and outdoor air pollutants, and heat.

Energy use in buildings also contributes to outdoor urban air quality problems via the power plant emissions associated with delivering electricity to buildings. Energy use in buildings can influence outdoor air quality in cities in other more subtle ways also. For example, since the emission of waste heat from buildings warms the urban environment it affects the rate constants in many of the equations that influence the formation and destruction of tropospheric ozone. The elevated urban air temperature also affects emissions of pollutants from both biogenic and anthropogenic sources. Under warm atmospheric conditions, an increase in air temperature results in higher levels of hydrocarbon emissions (isoprene, monoterpenes) from vegetation. While this relationship is highly variable across plant species the sensitivity of biogenic emissions to increasing air temperatures is generally on the order of 5% per degree Celsius (Benjamin et al. 1996; Taha et al. 1998). Of course, under situations of extreme temperature stress (typically air temperatures above 38 °C) plant stomata begin to close up and the rate of biogenic emission can actually decrease as air temperature further increases.

Tropospheric ozone (O_3) and fine particulate matter (nominal sizes 2.5–10 μm – $PM_{2.5}$ and PM_{10}) are EPA-regulated criteria pollutants known to have detrimental health effects, including heart and lung disease, respiratory disease, and decreased lung function. Ozone is formed by chemical reactions involving oxides of nitrogen (NO_x) and volatile organic compounds (VOC) in the presence of sunlight. The precursors of ozone come from a range of anthropogenic sources including on-road motor vehicles, off-road vehicles, fugitive emissions, area sources, chemical solvents, power plants, and point sources. VOC emissions also come from biogenic sources. Particulate matter is generated both directly in the form of dust and soot from combustion processes and indirectly through reactions within the atmosphere (notably the formation of sulfate aerosols from SO_2 emissions at power plants, nitrates formed from NO_x, and organic aerosols in urban environments).

Both ozone and PM are influenced by a complex array of meteorological parameters that affect emissions, atmospheric chemistry, and transport (Bornstein and Thompson 1981; Sillman and Sampson 1995). Meteorological conditions are, in turn, affected by concentrations of ozone and PM. Atmospheric production of ozone and PM is strongly affected by ambient temperature (Vukovich 1994; Hubbard and Coburn 1998; Aw and Kleeman 2003) as a result of many interrelated factors, including the temperature sensitivity of emissions and reaction rates for relevant processes such as the decomposition of PAN (peroxyacetylnitrate) – an influential series of reactions in ozone formation. At the same time, higher temperatures can enhance the production of turbulent kinetic energy, vertical mixing, and the depth of the boundary layer (i.e., resulting in decreased concentrations). This relationship is further complicated by the local VOC:NO_x ratio which can lead to either decreases or increases in ozone concentrations depending on local conditions. Thus, waste heat emissions from buildings can influence the formation of ozone and PM in the urban airshed.

The water vapor mixing ratio also has a complex role in the photochemical production of ozone. On one hand it acts as a sink for NO_x and VOC (slowing the formation of ozone), but it is also a source for OH radicals (via chemical reaction with O) that together with NO_x act as catalysts for ozone formation (Singh et al. 1995; Muller and Brasseur 1999). Thus, the vast emissions of moisture from cooling towers that are commonly employed in larger commercial buildings may also contribute to this complex chemistry related to production of ozone.

3.12.5 Strategies for Sustainable Urban Development

Urban planners and regional government authorities are concerned about a host of environmental issues associated with urban development. These environmental challenges include local concerns such as air quality, water quality-availability, and energy availability. They also include more global concerns such as a city's contribution to global climate warming. The various policies, initiatives, and regulatory efforts that have been developed to address these issues are correspondingly diverse. These efforts include strategies to reduce energy consumption or shift energy production to cleaner sources. They also include efforts to modify surface characteristics through plot-level and city-scale development policies and regulations. Each strategy, regulation, or policy has the potential not only to affect its intended end point, but also can have unintended consequences in other aspects of the urban climate system. So, while the focus of this chapter is the many complex interactions between the urban climate system and building energy use, we must not lose track of the fact that there are many other aspects of the urban environment that also interact with these systems.

3.12.5.1 Building Energy Codes, Standards, and Rating Systems

Requirements for building construction are usually dictated by building codes developed and enforced at local or state levels. There is generally a code for the structural aspects of the building and a separate code for the energy performance characteristics. Energy codes are further differentiated by class of building (commercial or SFR) and climate zone. Energy codes are written in mandatory and enforceable language. They are typically informed by energy standards, which are guidelines or recommendations published by national organizations such as ASHRAE. Standards are routinely updated based on new findings in building science and technological innovations. The update cycle for the ASHRAE standard is 3 years. This standard makes recommendations regarding building characteristics such as insulation levels and equipment efficiencies, which can significantly affect building energy consumption. Further, it references other standards for a subset of specific characteristics such as ventilation. In an effort to provide a model energy code that can be readily adapted and implemented by local jurisdictions the International Code Council (ICC) updates their International Energy Conservation Code on a 3 year cycle. Many U.S. states have state energy codes that are based on some version of ASHRAE 90.1 or the IECC. In some cases, most notably California with its Title-24 energy code, the state code is more stringent than the current versions of ASHRAE 90.1 and IECC.

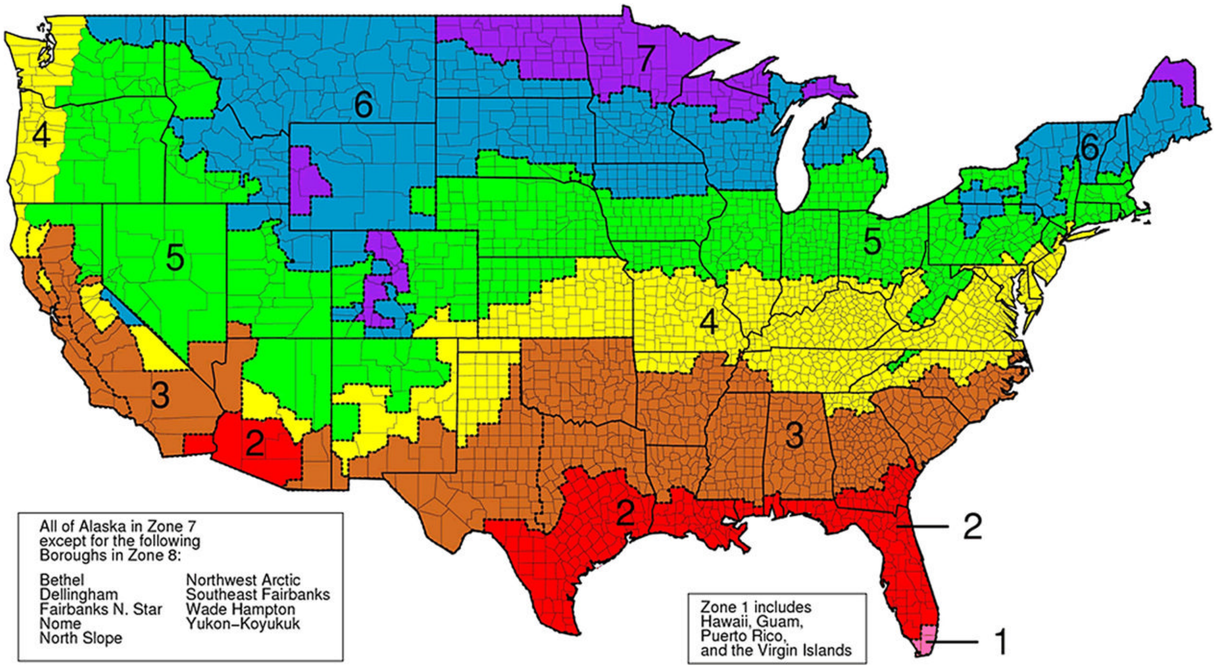

Figure 4 ASHRAE 90.1 climate zones in the United States. Reproduced from ASHRAE, 2007: *Standard 90.1: Energy Standard for Buildings Except Low-Rise Residential Buildings.* American Society for Heating, Ventilation, and Air-Conditioning Engineers, Inc, Atlanta, GA.

To account for variations in climate that differentially affect heating and cooling demand various energy codes and standards have different specifications for climatically different regions. ASHRAE 90.1 and IECC, for example, both define eight climate zones as illustrated in Figure 4. While all of California falls into five of these categories (2, 3, 4, 5, 6) the state of California in its Title-24 energy code uses a refined classification system that divides the state into 16 climate regions.

Beyond building codes there are also a host of voluntary standards and rating systems. For example, the Building Research Establishment's Environmental Assessment Method (BREEAM) was established in the United Kingdom in 1990 as a voluntary rating system for green buildings and is updated regularly. France has a similar standard – the Haute Qualite Environmentale (High Environmental Quality) or HQE – introduced by the Centre Scientifique et Technique du Batiment (CSTB). Australia has its Green Star rating system launched in 2003 by the Green Building Council of Australia. Leadership in Energy and Environmental Design (LEED), developed by the U.S. Green Building Council, is popular in the US, but has been applied to buildings in many countries. Green Globes, developed by the Green Building Initiative – a Portland, Oregon-based nonprofit – is also a popular rating system that has been widely used in Canada. Other rating systems exist around the world. All tend to have common features related to assessing building energy efficiency. They establish a baseline reference building and then rate a current building design with respect to its predicted or actual energy consumption. One drawback of most such rating systems is that building energy assessment is based on predictive energy simulation models rather than being based on actual (post-occupancy) performance. Actual building energy performance can deviate significantly from such predictions as a function of how well individual systems actually perform (typically determined through building commissioning), and how building occupants and managers interact with the building's systems (Newsham et al. 2009; Scofield 2009).

As these codes, standards, and rating systems evolve in conjunction with government initiatives they continue to move the building industry toward net-zero energy buildings of the future. Of course, regardless of the pace of such improvements in energy standards, the longevity of existing buildings will inevitably temper the pace of reduction in energy use across the entire building sector. Many individual systems such as roofing membranes and mechanical equipment have lifespans ranging from 15 to 30 years. The lifespan of the building itself varies substantially, but can range anywhere from several decades to more than 100 years. Thus, in the absence of deep retrofits, the penetration of new technologies and new building energy codes and standards has a correspondingly long time scale. Nevertheless, new codes and government initiatives hold promise for substantially reducing the energy consumption of new buildings. For example, the California Energy Commission has a stated goal of having net-zero new construction in the residential sector by 2020 and net-zero energy consumption in new commercial construction by 2030. This and similar efforts around the world have been motivated by concerns over fossil-fuel contributions to climate and grand initiatives such as Architecture 2030, which seeks carbon neutral new buildings by 2030.

3.12.5.2 Innovations in Transmission and Distribution of Energy

The significant challenges of delivering electricity to an ever-urbanizing world subject to the stresses of climate, population growth, and increasing per capita consumption is stretching capacities both in terms of power generation and transmission infrastructure. Aside from end-use efficiency, cities and regions are increasingly turning to new promising solutions. One approach that has received tremendous attention in the popular media is the notion of the 'smart grid.' The smart grid includes several interconnected components. First, is improved transmission–distribution of electrical energy through use of digital technology to enable real-time management of transmission networks. These modernized networks are then linked to management of end-use loads through smart meters and grid-enabled appliances, which exchange information with the grid, reducing or delaying energy consumption in response to price or load signals from the smart grid. To the extent that such technologies reduce and shift peak loads, they also shift the associated waste heat emissions. While innovations in the electric utility infrastructure will take place at regional scales, and building energy use improvements will take place at the building scale, there will likely also be innovations at the neighborhood scale. For example, there is growing interest in district heating and cooling strategies. District heating and cooling replaces individual chillers and boilers in buildings with a central facility that provides steam or chilled water to a small network of buildings located in close proximity. Such systems can improve overall efficiency for the neighborhood and also reduce capital costs of equipment, but they result in a centralized and concentrated emission of pollutants and waste heat.

3.12.5.3 Urban Design, Land Use, and Surface Characteristics

The characteristics of urban design that are most influential in the urban climate system include infrastructure characteristics such as the morphology of buildings that comprise the urban landscape (e.g., heights of buildings, widths of 'canyons' between buildings), and surface characteristics ranging from rooftop albedo to street-level vegetative cover and prevalence of impervious surfaces. Changes to these characteristics affect energy consumption in cities through both direct mechanisms (e.g., reduced heat conduction through highly reflective roofs), but also through indirect mechanisms (e.g., higher vegetative cover in a city can reduce air temperature, leading to reduced air conditioning demand via mechanisms of convection and infiltration).

Urban vegetation and albedo have long been strategies investigated for UHI mitigation (e.g., Rosenfeld et al. 1995; Taha et al. 1998; Taha and Sailor 1997). The motivation for studying these strategies arises directly from the surface energy balance for a city. For example, consider a control volume around the air of a city as illustrated in Figure 5, where Q^* is the net radiation term, Q_L is the latent heat flux from the urban surface, Q_H is the sensible heat flux from the urban surface, Q_A is the net advection of heat (enthalpy) into the control volume, Q_G is the conduction of heat into the substrate (including building materials), and Q_F is the anthropogenic heat

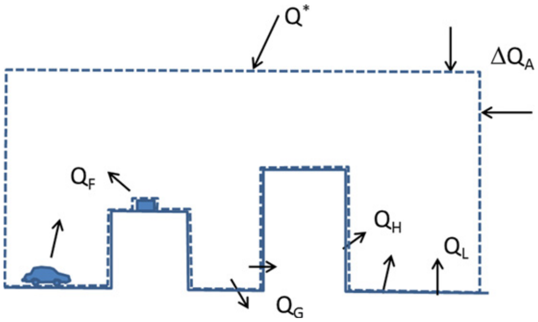

Figure 5 Key contributors to the energy balance of an urban surface (ground, walls and roofs) and the volume of air (bounded by the dashed line) above the urban surface.

generation which can be treated as a source term in the control volume. The net radiation term encompasses incoming and outgoing energy both in the short wave spectrum (solar radiation) and the long wave spectrum (thermal radiation). Depending upon time of day and season, this net radiation term, which includes incoming, emitted, and reflected components may be positive or negative. Most of this radiant energy is transmitted through the urban canopy air volume (defined here as being nominally twice the average building height above the ground surface), with a small amount being absorbed directly by the air molecules in this layer. The sensible and latent heating terms account for convection and evapotranspiration processes at the surface, respectively. Some sensible and latent heat crosses the control volume as part of the net advection term. The anthropogenic heat flux term can be thought of as a source term in the volume that accounts for emission of heat from vehicles, building HVAC systems, and other sources, including human metabolism of individuals within the street canyons. The rate of rise of air temperature in the control volume can then be computed from the sum of the sensible forms of heat fluxes into the air volume:

$$\rho C V \frac{\partial T}{\partial t} = Q_F + Q_A + Q_H \tag{7}$$

where ρ is the air density, C is the specific heat, V is the air volume, $\partial T/\partial t$ is the time rate of change of air temperature in the volume. In this equation Q_F, Q_A, and Q_H are rates of heat addition for anthropogenic heat, advection, and sensible heat exchange processes, respectively. All are in units of W.

It should be noted that evaporation and transpiration processes can be significant contributors to the surface energy balance (Q_L), but are only indirectly reflected in the above temperature evolution equation through their influence on other components of the volumetric energy balance. Likewise, net radiation (Q^*) is not directly included in this equation, although it plays a driving role in affecting surface sensible flux, and also can contribute to a modest amount of warming of the air through absorption of radiative energy within the air column (ignored here for simplicity, but treated as a volumetric source term in a thorough treatment of the energy balance). Thus, in evaluating the role of the urban surface in the elevation of urban air temperatures and heat island development it is also important to consider the surface energy balance, which results from Figure 5.

$$Q^* = Q_H + Q_L + Q_G \tag{8}$$

Again, in this expression each term must be expressed in units of W. This is necessary as the corresponding fluxes [W m^{-2}] each act over different surface areas. It must also be recognized that the values of each heat flux vary in space (and time) across the urban surface (e.g., there is very little storage heat flux Q_G into window glass, higher sensible heat fluxes from warmer surfaces, etc). In practice, eqns [7] and [8] are solved in fully three-dimensional atmospheric models, subject to atmospheric initial and boundary conditions and with the aid of boundary-layer parameterizations that evaluate the sensible and latent heat flux terms as functions of atmospheric stability. When including anthropogenic heating in the surface air energy balance it must be noted that the vertical distribution of anthropogenic heat emission is important. Specifically, while vehicles emit heat into the air at pedestrian level, emissions from a building occur throughout the vertical height of the building, with a substantial portion occurring at the location of the mechanical HVAC equipment – often located on the roof. Thus, while vehicle emissions of anthropogenic heat may be considered to be well mixed within the urban canopy, heat and moisture emissions from the building sector occur within and above the urban canopy. As a result, some of the building's anthropogenic emissions may have little impact on the air temperatures within the canyon.

There are several methods for investigating the urban air temperature sensitivity to changes in surface parameters, and, hence, the efficacy of UHI mitigation measures. These include field measurements in full-scale deployments of mitigation measures and computer simulation of simplified scenarios of surface modification. Both have significant limitations. For example, in conducting large-scale controlled experiments to explore the effects of heat island mitigation strategies such as increasing surface albedo across the city, it is difficult to measure resulting effects on neighborhood air temperature which may be small relative to measurement uncertainties and spatial variability. Furthermore, it can be difficult to attribute measured differences in air temperatures to a particular surface modification when many other factors (e.g., synoptic weather, anthropogenic emissions) covary. Nevertheless, some researchers have investigated UHI mitigation measures indirectly by making detailed urban air temperature measurements in conjunction with statistical analyses of land use and land cover variation across the city (e.g., Hart and Sailor 2009). The resulting regression models can provide insight into the potential for surface modification to reduce the magnitude of the UHI.

Numerous studies have tried to estimate the efficacy of UHI mitigation strategies by using regional scale (mesoscale) atmospheric models. Such efforts are inevitably limited by the inability of most regional models to resolve individual buildings and the complexities of heat transfer and fluid flow within the urban canopy. Rather, such studies often apply a simple uniform change to a surface characteristic such as albedo and compare the resulting 2-m predicted air temperature with that predicted by the model prior to the surface modification. While canopy-layer and computational fluid dynamics models can resolve effects of surface modification on near surface air temperatures within realistic urban canopies, they generally have simplified coupling with regional climate, and so estimation of regional-scale effects of large-scale UHI mitigation is still limited.

Morphology of urban canyons – building height to canyon width ratios – also has the potential to affect near-surface environmental conditions and the UHI more generally. This occurs through a combination of three factors. First, tall buildings provide shading to the urban surface below so that much of the radiative load from the sun is intercepted by building roofs and exterior walls. Depending upon the albedo of roof-wall surfaces and the fractional window area and glazing characteristics, this radiative load is largely reflected out of the urban canyon, or conducted-transmitted into the building – later reentering the urban energy balance at the location of the HVAC heat exchangers (e.g., roof-mounted packaged air conditioning units). The second role that morphology plays in the urban energy balance is that of affecting the exchange of long wave radiation among multiple urban surfaces and the sky. As a result, the floor of the urban canyon tends to remain warmer at night than its nonurban counterpart. Finally, the layout of buildings in a city can significantly affect transport of pollutants and the ventilation of urban canyons, depending upon their orientation relative to the prevailing wind direction. Through these mechanisms the morphology of urban canyons can be an important factor in determining street-level climatic conditions. For example, simulations conducted by Emmanual and Fernando (2007) found that high-density development was more effective than high-albedo UHI mitigation in terms of overall reductions in air temperature and mean radiant temperatures within an urban canyon. It is important to note, however, that compact development – as with any sustainable development strategy – has both beneficial and detrimental consequences. For example, deeper urban canyons can result in more stagnant air mass near the surface and correspondingly higher levels of pollutants.

3.12.6 Vulnerabilities and Opportunities Moving Forward

It should be clear from the preceding discussion that there are many complex interactions between the urban climate system and energy use in the building sector. Climate variability and climate change affect energy consumption for heating and cooling. The energy use in buildings provides a feedback mechanism whereby the urban climate is further perturbed. Additionally, energy use in the building sector has regional and global climate consequences associated with the emissions of pollutants, including carbon dioxide, from power plants.

The multitude of interconnections between energy and climate suggests a need to tread carefully with respect to physical or social engineering of the urban climate system as societies attempt to mitigate the adverse environmental consequences of development. For example, UHI mitigation efforts intended at reducing air temperatures for the purpose of reducing heat-related morbidity and mortality may result in thinner mixing heights over urban areas. Under such conditions, any moisture emissions at the surface are then mixed into a smaller volume of air, resulting in higher levels of near-surface humidity – and a mechanism for increasing heat-related morbidity and mortality, despite reductions in air temperatures. Likewise, UHI mitigation may inhibit ventilation of the urban canopy, creating a mechanism for worsening air quality. There are numerous other examples where UHI mitigation strategies may have unintended consequences. Thus, it is particularly important that as urban climate mitigation-adaptation policies and initiatives are proposed, they should be scientifically, socially, and economically vetted in terms of their potential wide-ranging consequences – intended or otherwise.

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Glossary

Diesel particulate filter (DPF) A device designed to remove diesel particulate matter from the exhaust gas of a diesel engine.

Greenhouse effect The phenomenon whereby the Earth's atmosphere traps solar radiation, caused by the presence in the atmosphere of gases such as carbon dioxide, water vapor, and methane that allow incoming sunlight to pass through but absorb heat radiated back from the Earth's surface.

Plug-in hybrid vehicle (PHV) A hybrid vehicle that utilizes rechargeable batteries, or another energy storage device, that can be restored to full charge by connecting a plug to an external electric power source (usually a normal electric wall socket).

Sustainable development Development that meets the needs of the present without compromising the ability of future generations to meet their own needs. It contains within it two key concepts: (1) the concept of needs, in particular the essential needs of the world's poor, to which overriding priority should be given and (2) the idea of limitations imposed by the state of technology and social organization on the environment's ability to meet present and future needs.

Sustainable transportation Transportation that refers to any means of transport with low impact on the environment.

Three-way catalyst (3WC) An oxidation–reduction catalytic converter installed in the exhaust pipe system of gasoline vehicles. It is designed to do three simultaneous tasks: (1) Reduction of nitrogen oxides to nitrogen and oxygen, (2) Oxidation of carbon monoxide to carbon dioxide, and (3) Oxidation of unburned hydrocarbons (HC) to carbon dioxide and water.

Transportation fuel Any material (mainly gas or liquid) burned to produce power to motor vehicle.

> Surprised by joy – impatient as the Wind
> I turned to share the transport
> William Wordsworth, *Desideria*

3.13.1 Introduction

Secure, protected, clean, low-cost and affordable energy and transportation are substantive to the social and economic vitality of the world. Our quality of life is heavily dependent on economical, plentiful, and reliable supplies of energy; nearly everything that defines our way of life requires some sort of energy-consuming device. In parallel, few (if any) human activities seem more important to civilization than transportation and communication, and, apart from direct tyranny and oppression, nothing is more harmful to the well-being of a society than an irrational transportation system.

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Growth in economic activity and population are the key factors that determine transportation sector energy demand. Transportation is an important part of economy and functions as one of its foundation, support, and service provider. Subsequently, modern mobile societies consume significant amounts of energy to support passenger travel and freight transport. In developing economies, increased economic activity leads to growing income per capita; and as standards of living rise, demand for personal transportation increases. More specifically, the magnitude of the mobility of persons and freight and the vast trip distances generated by such hypermobility makes transportation the fastest growing consumer of energy and producer of greenhouse gases (GHGs) (EC 2010; TRB 2011).

Energy for transportation vehicles can be supplied externally (e.g., sailboats, electric trains, trolleys) or carried on board (e.g., automobiles, jet aircraft). In the twentieth century, the internal combustion engine (ICE) became the predominant source of power for transportation vehicles, displacing animal, wind, and steam power. After a brief period of experimentation early in the twentieth century, liquid fuels derived from petroleum emerged as the clearly preferred form of energy for ICEs. These fuels have four key advantages: (1) they have high energy density per volume and weight; (2) they are easily handled and stored because they are liquid under ambient conditions; (3) throughout most of the twentieth century, petroleum resources have been in abundant supply; and (4) they are relatively inexpensive. By the middle of the twentieth century, petroleum supplied 90% of the energy for transportation vehicles and continues at the same percentage approximately.

Today, a variety of opportunities exist to alter future demand for transportation fuels, reduce emissions, improve energy security, and provide significant energy savings. On the engine front, they include all-electric, full hybrids, plug-in hybrids, and hydrogen fuel cell drive trains. On the fuel side, the path moves through dieselization, biofuels (i.e., ethanol, biodiesel), natural gas, and coal-to-liquid fuels and hydrogen. All of these go some way to address air quality problems and to make an impact on GHG emissions in the developed world. But it merely scratches the surface of the problems just outlined for the developing world, where climate issues fall low on its list of priorities. In this global framework, petroleum fuels seem to continue as the dominant transportation fuel in the short and medium term.

At the same time, the world is concerned about the transportation industry for its huge consumption of petroleum energy as well as for its environmental impact. Governments, the transportation industry, and experts participate in the discussion to explore alternatives. Policy makers are confronted with difficult decisions on how to respond to climate issues. Policy making in this field is particularly challenging because of the high degree of uncertainty encompassing this kind of decision making. Uncertainty pertains to several key factors: the impacts climate will have on nature, society, and the economy, and the cost and effects of policies designed for mitigation. In any case, the types of policy measures taken to satisfy treaty targets will have lasting impacts on the technology we use and could affect the way we live, consume, and travel.

In the following, based on the bottom-up approach, we first discuss the energy consumption by transportation (current and projected) and then we proceed to the next chapter by presenting and discussing the status of transportation emissions. In Chapter 3 we focus on social and environmental problems induced by transportation (at the local and the global scale). In Chapter 4 we discuss the mitigation actions implemented so far and conclude with a short commentary on the future potential.

3.13.2 Energy Consumption by Transportation

Forecasts for the world population indicate that it will exceed 9 billion people in 2050 (UN 2011). The largest percentage of this growth is taking place in the developing world combined with an increased urbanization and demand for energy and transportation. No one knows how long the world's oil reserves will last, but even the oil industry suspects the world oil peak is now approaching. The extent to which conventional nonrenewable fossil fuels will continue to be the primary resources for nearly all transportation fuels is subject to debate. Some studies estimate global resources for oil at about a trillion barrels. This represents 30 years of reserves at the present rate of consumption (Rodrigue et al. 2009). According to BP (BP 2011b), proved oil reserves in 2010 were sufficient to meet 46.2 years of global production. But the gap between demand and supply is narrowing, an effect compounded by the peaking off of global oil production. The steady surge in demand from emerging economies requires a significant additional output. This raises concern about the capacity of major oil producers to meet this rising world demand. The producers are not running out of oil, but the existing reservoirs may not be capable of producing on a daily basis the increasing volumes of oil that the world requires.

World liquids production in 2035 will exceed the 2008 level by 26.6 million barrels per day, with production increases expected for both Organization of the Petroleum Exporting Countries (OPEC) and non-OPEC producers (**Figure 1**). Overall, 57% of the total increase is expected to come from non-OPEC areas, including 31% from non-OPEC unconventional liquids production alone. OPEC will produce 46.9 million barrels per day in 2035, and non-OPEC producers will provide 65.3 million barrels per day. Increasing volumes of conventional liquids (crude oil and lease condensate, natural gas plant liquids and refinery gain) from OPEC members contribute 10.3 million barrels per day to the total increase in world liquids production from 2008 to 2035, and conventional liquids supplied from non-OPEC nations contribute 7.1 million barrels per day. Unconventional liquids production increases by about 5% annually on average over the projection period, because sustained high oil prices make unconventional liquids more competitive, and 'above-ground' factors ('Above-ground' factors refer to those nongeological factors that could affect supply, including but not limited to government policies that limit access to resources; conflict; terrorist activity; lack of technological advances or access to technology; price constraints on the economic development of resources; labor shortages; materials shortages; weather; environmental protection actions; and short- and long-term geopolitical considerations (USEIA, 2011)) limit the production of economically competitive conventional liquids. Unconventional fuels account for 35% (9.2 million barrels per day) of the increase in total liquids production in the US Energy

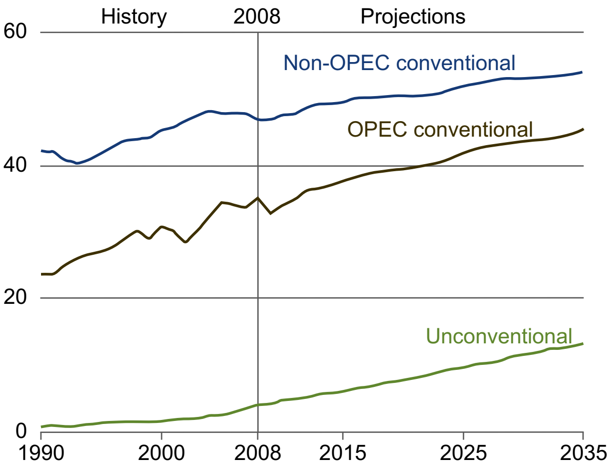

Figure 1 World total liquid fuels production for the period 1990–2035 (million barrels per day). Source: US Energy Information Administration (USEIA), International Energy Outlook 2011 (IEO2011). [Available online at http://www.eia.gov/forecasts/ieo/world.cfm.] Assessed at 02/02/2012.

Information Administration (USEIA 2012) reference case, and 8.2 million barrels per day of the increase in unconventional supply comes from non-OPEC sources.

Transportation consumes more than 50% of world of liquid fuels and its share tends to increase in the future (Hirsch et al. 2005). Estimations say that growth in transportation energy use from 2008 to 2035 will account for 87% of the total increase in world liquid fuels consumption (Figure 2). Most of the growth is expected among the developing non-OECD (Organization for Economic Co-operation and Development) nations, whereas consumption among the developed OECD nations is projected to remain relatively flat or decline. In 2008, non-OECD countries as a group consumed 34% less energy for transportation than OECD countries. In 2035, non-OECD energy use for transportation will probably exceed that in the OECD countries by 19% (Table 1).

The relationship between transportation and energy is a direct one, but subject to different interpretations because it concerns different transport modes, each having a specific performance level (Rodrigue et al. 2009). There is often a compromise between speed and energy consumption, related to the desired economic returns (Figure 3). Passengers and high-value goods can be transported by rapid but energy-intensive modes because the time component of their mobility tends to have a high value, which conveys the willingness to use more energy. Economies of scale, mainly those achieved by maritime transportation, are linked to low levels of energy consumption per unit of mass being transported, but at a lower speed. This fits relatively well with freight transport imperatives, particularly bulk. Comparatively, air freight has high energy consumption levels linked to high-speed services.

Energy use in the transportation sector includes energy consumed in moving on land (road, rail, pipelines), water (maritime), and air (aviation). Each of the transportation components is characterized by specific characteristics (Rodrigue et al. 2009):

- Land transportation accounts for the great majority of energy consumption – about 85% of the total energy used by the transport sector in developed countries. This trend is not, however, uniform within the land transportation sector itself, because road transportation is almost the sole mode responsible for additional energy demands over the last 25 years. Despite a falling market share, rail transport, on the basis of 1 kg of oil equivalent, remains four times more efficient for passengers and twice as efficient for freight movement than road transport. Rail transport accounts for 6% of global transport energy demand.

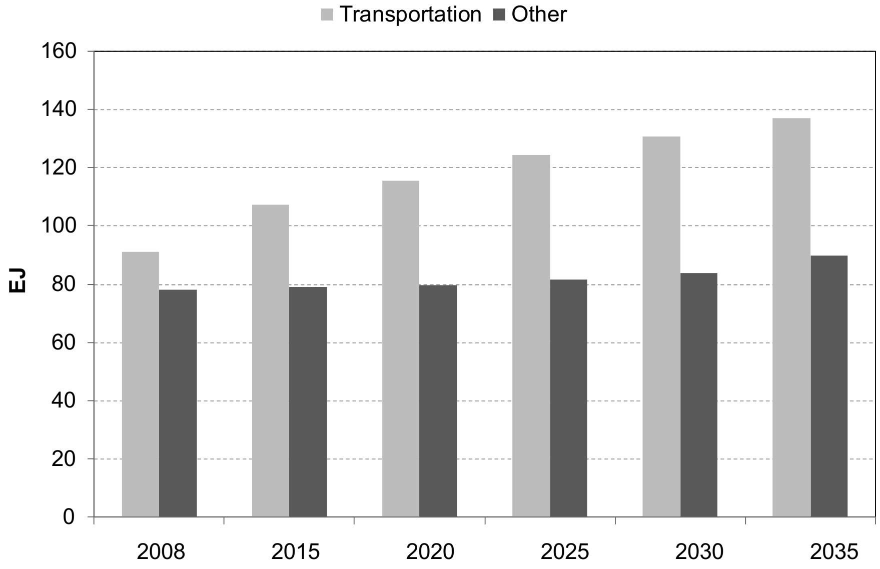

Figure 2 World liquid fuels consumption by end-use sector for the period 2008–35. Source: US Energy Information Administration (USEIA), International Energy Outlook 2011 (IEO2011). [Available on line at http://www.eia.gov/forecasts/ieo/world.cfm.] Assessed at 02/02/2012.

Table 1 Transportation energy use by region, 2008–35 (exajoules)

Region	*2008*	*2015*	*2020*	*2025*	*2030*	*2035*	*Average annual % change, 2008–35*
OECD	**62.6**	**63.7**	**64.6**	**65.3**	**66.7**	**68.4**	**0.3**
Americas	35.0	36.0	36.5	37.2	38.4	40.1	0.5
Europe	19.8	19.7	19.8	19.7	19.9	114.9	0.0
Asia	7.8	7.9	8.2	8.3	8.3	8.3	0.3
Non-OECD	**41.0**	**54.5**	**61.9**	**70.9**	**77.3**	**81.6**	**2.7**
Europe & Euroasia	7.6	8.2	8.5	9.0	9.6	10.0	1.1
Asia	17.2	27.5	33.4	40.0	42.9	44.5	3.8
Middle East	53.7	6.4	6.6	7.6	9.2	10.0	2.3
Africa	3.8	4.0	4.2	4.6	5.1	5.6	1.6
Cent. & S. America	6.8	8.1	9.1	9.7	10.6	11.3	2.0
World	**103.6**	**118.26.6**	**126.5**	**136.2**	**114.0**	**149.9**	**1.5**

Source: US Energy Information Administration (USEIA), International Energy Outlook 2011 (IEO2011). [Available on line at http://www.eia.gov/forecasts/ieo/world.cfm.] Assessed at 02/02/2012.

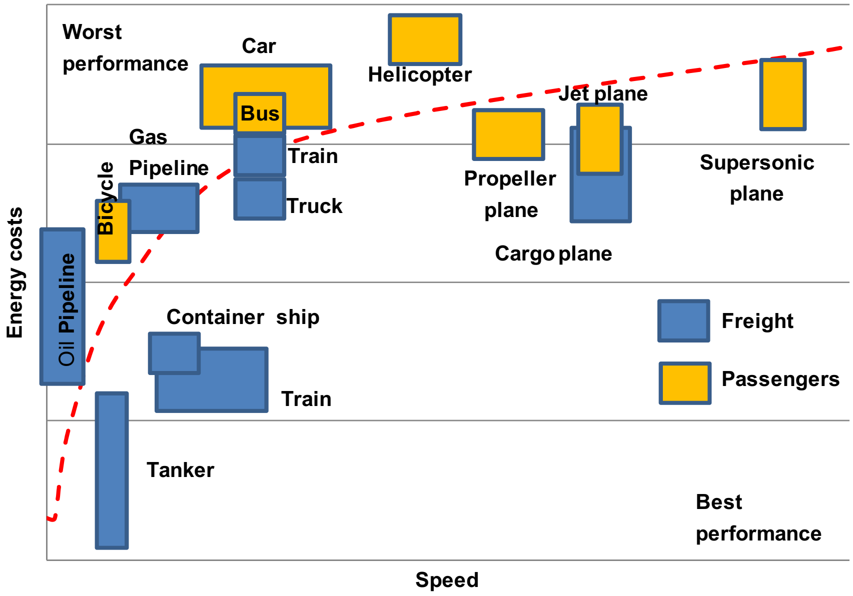

Figure 3 Transportation modes and energy. Source: Rodrigue, J.-P., C. Comtois, and B. Slack, 2009: *The Geography of Transport System.* 2nd ed. Routledge, New York.

- Maritime transportation accounts for 90% of cross-border world trade as measured by volume. The nature of water transport and its economies of scale make it the most energy efficient mode because it uses only 7% of all the energy consumed by transport activities, a figure way below its contribution to the mobility of goods.
- Air transportation accounts for 8% of the energy consumed by transportation. Air transport has high energy consumption levels, linked to high speeds. Fuel is the second most important budget for the air transport industry, accounting for 13–20% of total expenses. This accounts for about 1.2 million barrels per day. Technological innovations, such as more efficient engines and better aerodynamics, have led to a continuous improvement of the energy efficiency of each new generation of aircrafts.

All those listed, almost entirely, rely on oil. The only exception to this is electric rail transport, which uses for a considerable share other energy sources, like hydro or nuclear power, depending on the energy mix in electricity generation. As is clearly shown in various future projections, energy use by every transport mode is expected to keep on growing at a similar rate as in the last decades of twentieth century and to double between 2000 and 2040 (Figure 4).

A primary factor in the projected increase of energy demand for transportation is the steadily rising demand for personal travel in both the developing and mature economies. In the developing economies, with gains in urbanization and personal incomes, demand for air travel and motorized personal vehicles increases. World vehicle ownership is projected to grow rapidly – by 60% from around 1 billion today to 1.6 billion by 2030 (Figure 5), particularly in the non-OECD countries in which the vehicle population will rise from 340 million to 840 million over the next 20 years. In the industrialized OECD countries, growth in vehicle ownership

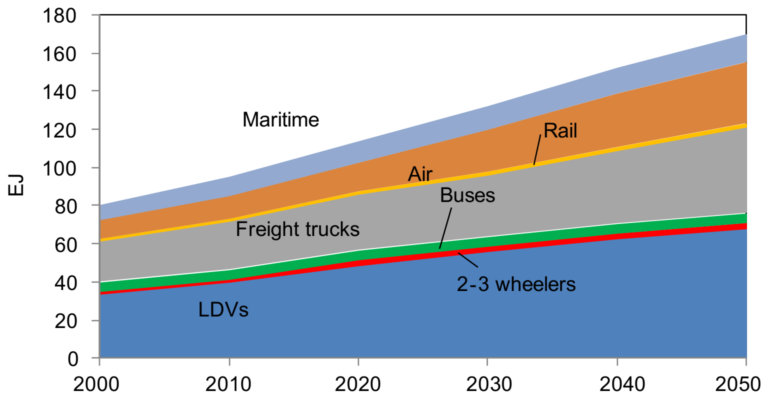

Figure 4 Projection of transport energy consumption by mode for the period 2000–50. Source: IPCC, 2007: Summary for policy makers. *Climate Change 2007: The Physical Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, et al., Eds., Cambridge University Press, Cambridge.

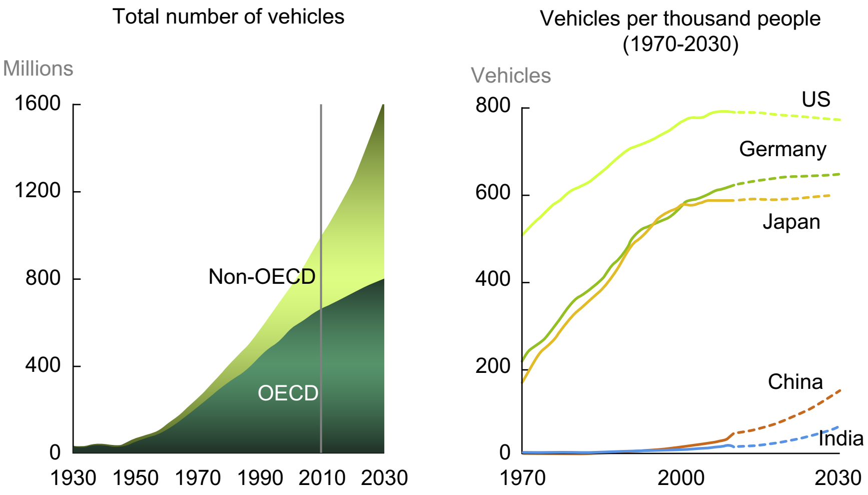

Figure 5 World vehicle population for the period 1930–2030 and vehicle density for the period 1970–2030. Source: BP Energy Outlook 2030, London, January 2011a. [Available on line at http://www.bp.com/liveassets/bp_internet/globalbp/globalbp_uk_english/reports_and_publications/statistical_energy_review_2011/STAGING/local_assets/pdf/2030_energy_outlook_booklet.pdf.] Assessed at 18/11/2011.

per capita slows as saturation levels begin to be reached. In most of the non-OECD countries, growth in vehicle ownership is expected to continue at a rapid pace. With higher economic growth rates and higher energy intensities, the non-OECD countries' share of world transportation energy demand rises from 40% in 2008 to 54% in 2035. In addition, strong GDP growth in the non-OECD economies leads to modal shifts in the transport of goods, and freight transportation by trucks leads the growth in non-OECD demand for transportation fuels.

3.13.3 Air Pollution and Climate

Current transport patterns, based primarily on private motorized vehicles, generate many social, environmental, and economic costs, accounting for more than half of global liquid fossil fuel consumption and nearly a quarter of the world's energy-related carbon dioxide (CO_2) emissions (IEA 2009). Transport is also typically responsible for around 80% of developing cities' local air pollution and more than 1.3 million fatal traffic accidents worldwide, most of which occur in developing countries (WHO 2009). Furthermore, the chronic traffic congestion caused by excessive motorization leads to lower productivity and reduced levels of accessibility in many of the world's urban areas. These patterns of transportation are expected to worsen under the continuous and rapid trend of motorization. There is a growing consensus by experts, policy makers, and the general public that these trends cannot continue without seriously affecting the economic viability and environmental quality of their cities and countries.

Emissions from energy and transportation systems are known to affect air quality, including photochemical smog, urban and regional haze, fine aerosol impacts on lung function, acid rain and acid deposition, greenhouse gas and aerosol impacts on climate, as well as stratospheric ozone depletion. Hence, the main socioenvironmental problems related with the consumption of petroleum fuels for transportation can be viewed at two scales:

1. The local scale: air pollution from vehicle exhausts that is harmful to human health, animals, and vegetation and,
2. The global scale: GHG emissions, mostly in the form of carbon dioxide (CO_2), that contribute to the earth's climate.

3.13.3.1 Air Pollution

3.13.3.1.1 Land Transportation

In most urban areas, emissions from increasing numbers of automobiles are a major contributor of harmful pollutants. Harmful primary pollutants are particulate matter (PM), carbon monoxide (CO), nitrogen oxides (NO_x), and non methane volatile organic compounds (NMVOCs) such as benzene and polycyclic aromatic hydrocarbons (PAHs). Sulfur dioxide and lead emissions from land transport have been strongly reduced and are now less relevant, at least in the developed world. Secondary traffic-related pollutants that often can extend from the local to the regional scale include gases such as ozone (O_3), peroxyacetyl nitrate (PAN), formaldehyde (HCHO), and secondary particles consisting of sulfate and nitrate organic compounds.

Road transport accounted for 22.5% and 21.2% of total global NO_x and PM emissions, respectively, in 2000 (Broken et al. 2007). **Figure 6** compares the worldwide evolution and trends of NO_x and PM emissions of road transport with those of all sources together (Metz 2005). Global emissions of NO_x and PM from road vehicles are projected to decrease by 65 and 53%, respectively, from 2010 to 2050 (significantly higher reductions from those corresponding to all sources emissions – 41% and 43% for NO_x and PM, respectively). These reductions are basically induced by considerable improvements in emissions factors; Takeshita (2011) reports over the same period reductions of 87% (NO*x*) and 91% (PM) (**Figure 7a-c**). Projections over shorter periods (2020) indicate that PM emissions reduction from road transportation will probably be masked by the increasing share of nonexhaust sources to the total emissions (Kousoulidou et al. 2008). However, despite the enormous technological progress made and optimistically projected, the continued growth in the number of vehicles and kilometers traveled as well as the existence of old and malfunctioning vehicles, make air pollution by motor vehicles a serious health concern, especially in the megacities of emerging economies (Baidya and Borken-Kleefeld 2009).

The railway sector emits significant amounts of NO_x (when compared with its share in the total energy use, in particular) as well as PM. As a result, emission standards that apply to all new and remanufactured locomotives have been established in both the United States and European Union (U.S. Department of Energy 2002). Exhaust aftertreatment devices for the reduction of NO_x (selective catalytic reduction, NO_x adsorber catalysts) and PM (catalyzed diesel particulate filters (CDPF)) have not been implemented in locomotive engine applications, but they may be necessary to meet future emission regulations. The railroad industry probably will be able to meet its near-term emissions regulations without resorting to aftertreatment devices, whereas the trucking industry required the devices earlier. Although the unique characteristics of locomotives may prevent direct transfer of the technologies developed for trucks, much can be learned from that industry.

Road traffic emissions comprise not only tailpipe exhaust emissions but also non exhaust emissions derived mostly from the vehicle-induced resuspension of dust deposited on the road and in part from the direct emissions from vehicle wear (brakes, tires, etc) (Thorpe and Harrison 2008). Non exhaust emissions are often of the same order or even greater than exhaust emissions, especially when rainfall rates are low and the wash-off of the road is reduced. Despite the high environmental and health burden of nonexhaust sources in urban environments, their emissions are often unknown and still uncontrolled. Because technological improvement will typically only affect 'tailpipe' emissions, the estimation of the nonexhaust part becomes increasingly relevant.

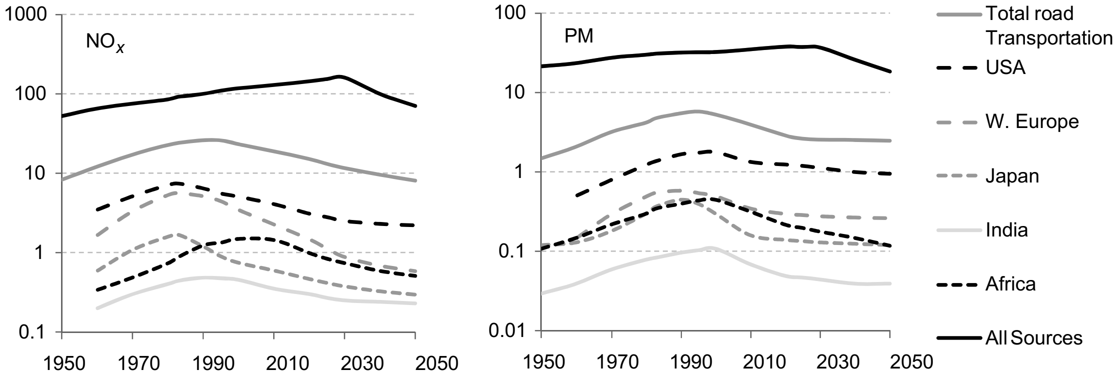

Figure 6 Trend of worldwide NO_x and PM emissions. Road transport and all sources (million of tons). Source: Metz, N., Worldwide emission trend 1950 to 2050. Road transport and all sources. Eurochamp Workshop in Andechs. Chemistry, transport and impacts of atmospheric pollutants with focus on fine particulates, 10–12 October 2005.

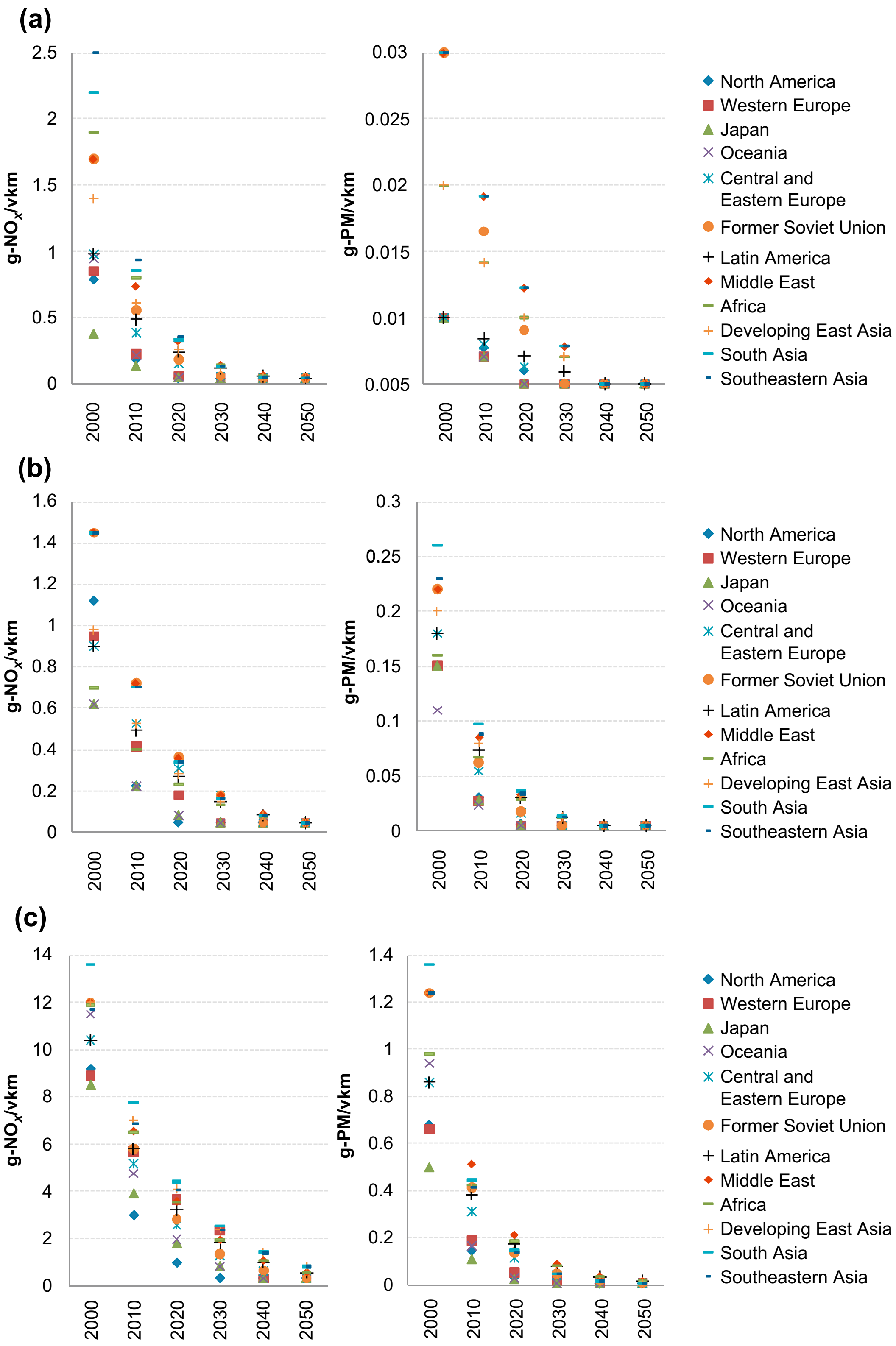

Figure 7 Projected NO_x and PM emission factors for gasoline ICE light-duty vehicles (a), diesel light-duty vehicles (b), and diesel heavy-duty trucks (c) by world region. Source: Takeshita, T., 2011: Global scenarios of air pollutant emissions from road transport through to 2050. *Int. J. Environ. Res. Pub. Health*, **8,** 3032–3062.

3.13.3.1.2 Maritime Transportation

Maritime is a very fuel efficient mode of transportation and is generally regarded as an environmentally friendly mode of transport. For some gases (i.e., SO_x), however, this mode causes more emissions per ton kilometer than other modes of transport (Eyring et al. 2010). Emissions from maritime transportation cannot be directly compared to emissions over land or within cities. The impact of emissions depends in part on where they take place and on where emissions are deposited. One argument is that they take place at sea and that their impact on air quality over land and within cities is negligible. However, this argument is not generally valid. About 70% of the emissions from oceangoing shipping occur within 400 km of the coastlines along the main trade routes (Corbett et al.1999). Moreover, a substantial part of maritime emissions takes place during operation within port. Ship maneuvering in harbors contributes about 6% of NO_x and 10% of SO_2 to total shipping emissions (Corbett and Fischbeck 1997). Besides maneuvering, loading and unloading of tankers also contribute substantially to harbor emissions because this is a highly energy consuming process (Wismann and Oxbol 2005). The harbor emissions often occur near major residential areas and can be transported far inland owing to local land–sea breeze winds. Thereby, ship emissions can have an impact on the air quality in coastal regions and may partly offset the decline of land-based sources and coastal pollution due to national control measures (Schlager and Pacyna 2004). On the global scale these effects are small, but could be more significant in shallower coastal waters where shipping is concentrated. **Figure 8** shows possible range of future NO_x, PM, and SO_x (a significant emission of maritime transportation due to high sulfur content of marine diesel) emissions according to four different technology scenarios and four different ship traffic demand scenarios (Eyring et al. 2005). The scenarios are based on assumptions on future ship traffic demand and technological improvements. The four future ship traffic demand scenarios are mainly determined by economic growth, which follows the IPCC Special Report Emission Scenarios storylines (IPCC 2009).

Inland shipping, that is, shipping on rivers and lakes, is not important in terms of emissions at the global scale. Emission estimates are not always comparable in different studies because the differentiation between ocean-going ships and inland shipping is not always sharp (Uherek et al. 2010). It is estimated that they are significantly less than road and air transport and comparable to those of rail transport (Ebert 2005).

3.13.3.1.3 Air Transportation

Air transport affects air quality in several ways. Its impact can be divided into the effects of aircraft emissions, which represent the major contributor to aviation-derived air pollution, and the lesser but nonetheless significant air pollution that occurs due to the operation of airports and their ancillary services. The impact of air transport on air quality is divided into direct and indirect effects (Daley 2010). Direct effects include emissions of air pollutants directly into the atmosphere, especially of NO_x and PM. In contrast, indirect effects occur when aircraft emissions initiate other physical or chemical processes that in turn cause air pollution, as when tropospheric ozone (O_3) is formed as a side-effect of NO_x emissions from aircraft and other airport-related sources.

NO_x emissions can be reduced by careful combustor design (Lee 2009), because of the fact that NO_x production tends to increase as an unintended consequence of the drive to achieve greater fuel efficiency; absolute NO_x emissions from aircraft are forecast to increase by a factor of approximately 1.6 between 2002 and 2025 (Daley 2010). These emissions are most concentrated in the vicinity of the runways, taxiways, and aprons of airports, as well as close to major roads. Recent work has demonstrated that exhaust pollutants may be transported to the ground far more effectively by aircraft wakes than by ambient atmospheric dispersion alone (Schürmann et al. 2007). Scientific assessments of PM emissions from aviation sources are characterized by greater uncertainty than are those of NO_x emissions; however, the contribution of airport sources to ambient concentrations of PM in areas adjacent to airports tends to be smaller than that of airport-derived NO_x (Daley 2010). The highest concentrations of aviation derived PM occur close to runways, taxiways, aprons and major roads; furthermore, as with NO_x, particles can be very effectively transported to the surface by aircraft wakes. PM emissions are forecast to increase over the period 2002–25 because of the difficulty of sustaining significant technology improvements in this area, meaning that aviation-derived particles are likely to remain an air pollutant of critical concern over the decadal timescale. **Figure 9** compares transportation related global annual emissions of NO_x, SO_2, and PM for the year 2000.

3.13.3.2 GHG Emissions

The primary GHGs produced by the transportation sector are CO_2, methane (CH_4), nitrous oxide (N_2O), hydrofluorocarbons (HFCs), and chlorofluorocarbons (CFCs). Water emissions at the Earth's surface have no climate effect. If released at cruise altitude by commercial aircraft, however, water vapor emissions can be more significant.

Globally, CO_2 accounts for 95% of transportation GHGs. HFCs, which are used in automobile, truck, and rail air conditioning and refrigeration systems, account for another 3% of transportation GHG emissions. N_2O and CH_4, which are both emitted as byproducts of combustion, account for the remainder of the transportation GHG emissions inventory. These emissions are all well-mixed in the atmosphere and long-lived, lasting from years to many decades. The long residence time requires that the historical development of emissions is taken into account when calculating the contribution to GHG enhancement and thus the radiative forcing at a given point in time. According to the World Energy Outlook 2009 (IEA 2009), global energy-related annual CO_2 emissions could increase to over 40 Gt by 2030 and transport emissions would make up over one fifth of that despite significant mitigation policies built into the reference scenario (**Figure 10**).

3.13.3.2.1 Land Transportation

Land transportation is, second to power generation, the largest emitter of CO_2 globally covering around 23% of the global total emissions in 2009 and the emissions are rising within the

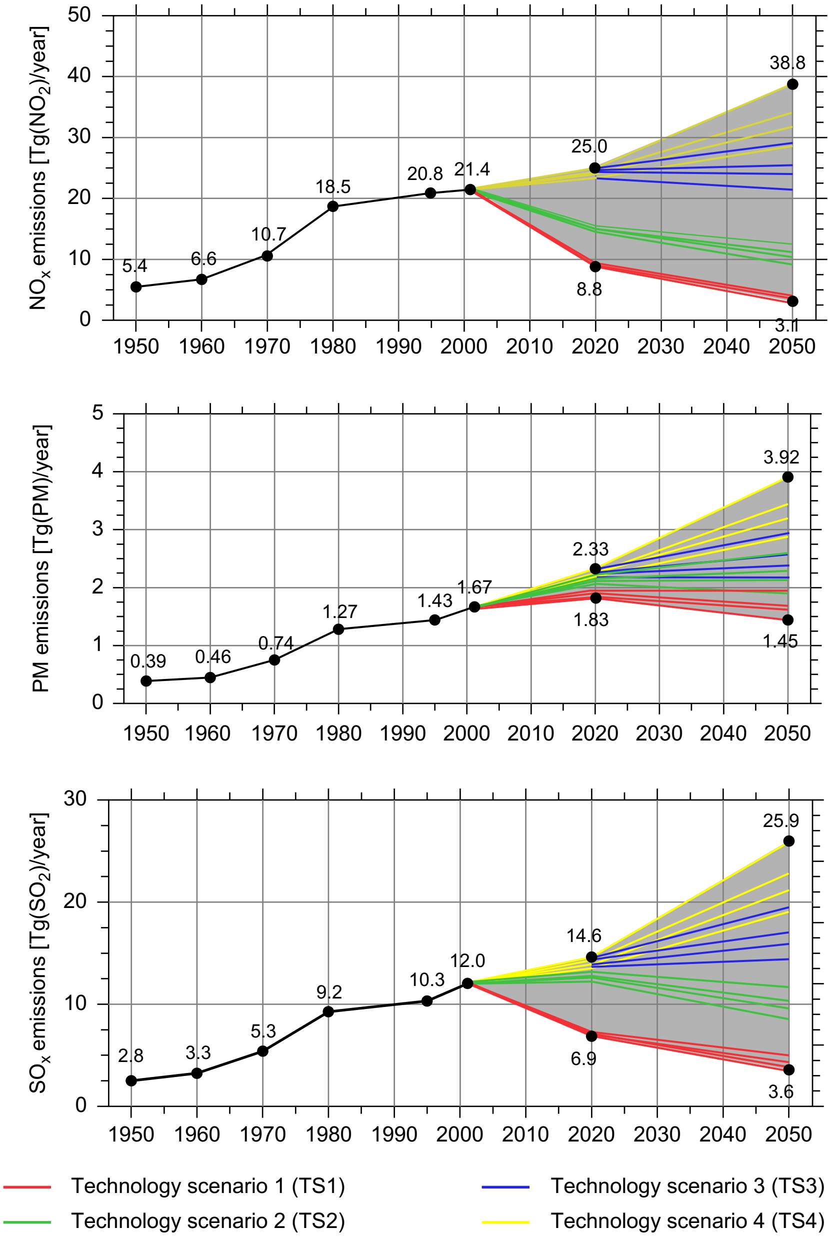

Figure 8 Possible range of future NO$_x$, PM, and SO$_x$ maritime missions according to four different technology scenarios (TSs) and four different ship traffic demand scenarios (DSs). Source: Eyring, V., H. W. Köhler, A. Lauer, and B. Lemper, 2005: Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050. *J. Geophys. Res.*, **110,** D17306.

entire period 1990–2009 (with a small decrease of 1.7% in 2008) (Olivier et al. 2011). (Other sources include industrial processes, agricultural processes, fossil fuel retrieval, processing and distribution, residential and commercial sources, land use and biomass burning, waste disposal and treatment.) Land transportation accounted for 4.58 Gt (1990) and 6.54 Gt (2009), representing an increase of approximately 43% (Figure 11). Within road transport, automobiles and light trucks produce well over 60% of emissions, but in low- and middle-income developing countries, freight trucks (and in some cases even buses) consume more fuel and emit more CO$_2$ than the automobiles and light trucks.

Although there is yet no global-gridded rail inventory available, this sector is certainly the lowest CO$_2$ emitter (in terms of 'tailpipe' emissions at least) because it has been to a large extent electrified (in Europe, for example, diesel-powered vehicles currently account for around 20% of operations (UIC 2010)). Available studies show that rail emissions make up only 1–3% of the total transportation emissions (EEA 2003; AAR 2011).

3.13.3.2.2 Marine Transportation

Estimates for the global CO$_2$ emissions for maritime differ substantially depending on the approach (bunker fuel statistics

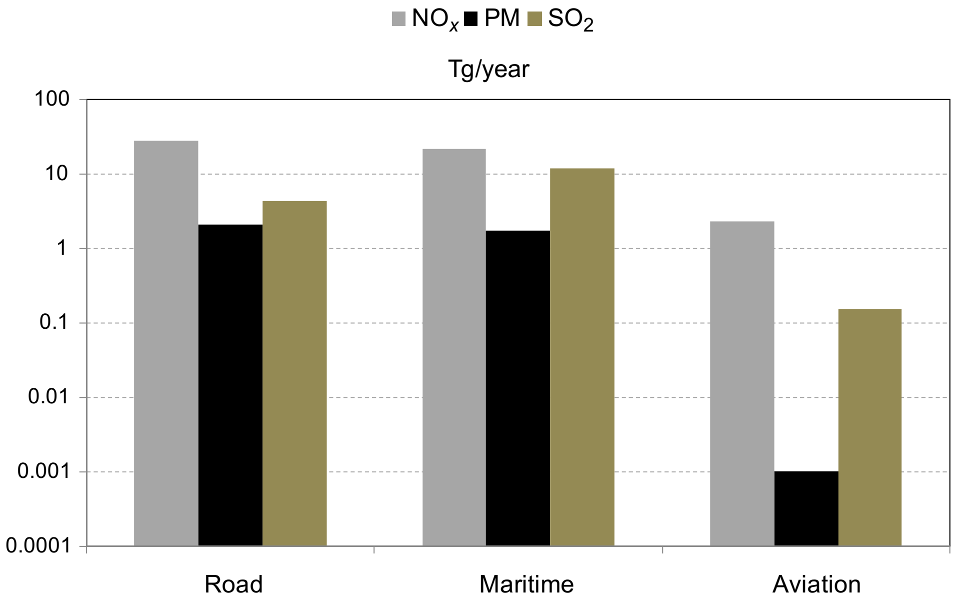

Figure 9 Transportation-related gobal annual emissions of NO$_x$, SO$_2$, and PM estimated for the year 2000.

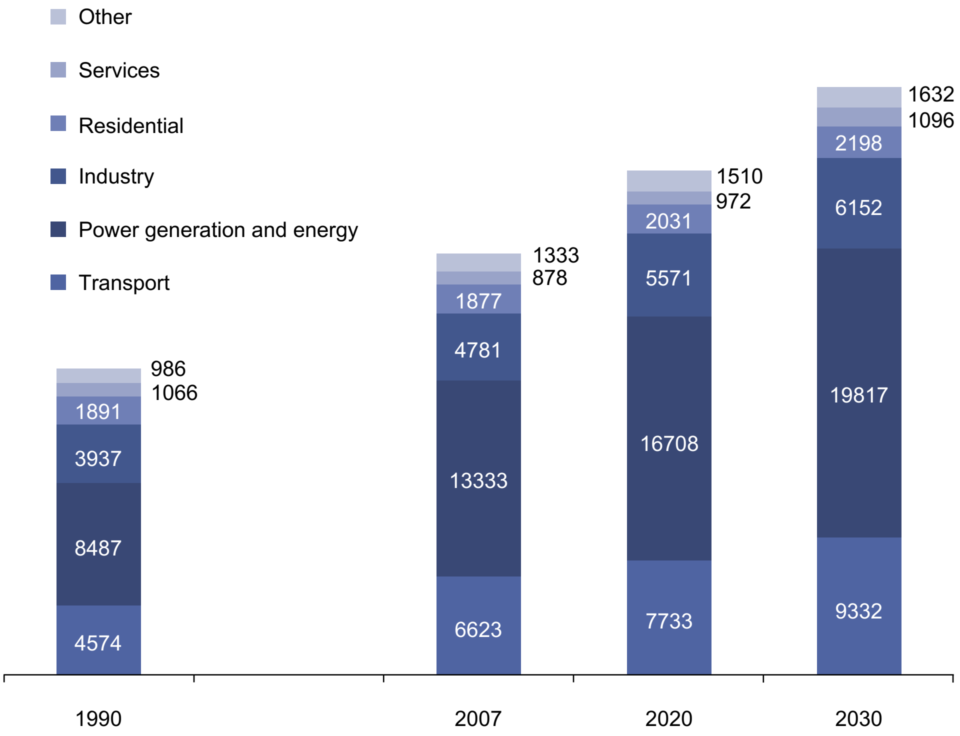

Figure 10 Historical and projected world energy-related CO$_2$ emissions (Mt). Source: IEA, 2009: World energy outlook 2009. [Available on line at http://www.iea.org/textbase/nppdf/free/2009/weo2009.pdf] Assessed at 02 Feb 2012.

or activity based figures). For year 2000 for example, estimates range from 501 to 960 Tg (Eyring et al. 2010). Recent studies reveal converging estimates of current ship emissions and suggest that oceangoing ships emitted around 800 Tg CO$_2$, contributing around 2.7% to all anthropogenic CO$_2$ emissions in 2000 (Eyring et al. 2010). Figure 12 shows possible range of future CO$_2$ emissions according to four different technology scenarios and four different ship traffic demands.

Emission equivalent of CFCs from the world shipping fleet is very uncertain and it has been estimated (on annual global emissions) from around 1–3% to 10% for the year 1990 and data have not been renewed (Eyring et al. 2010).

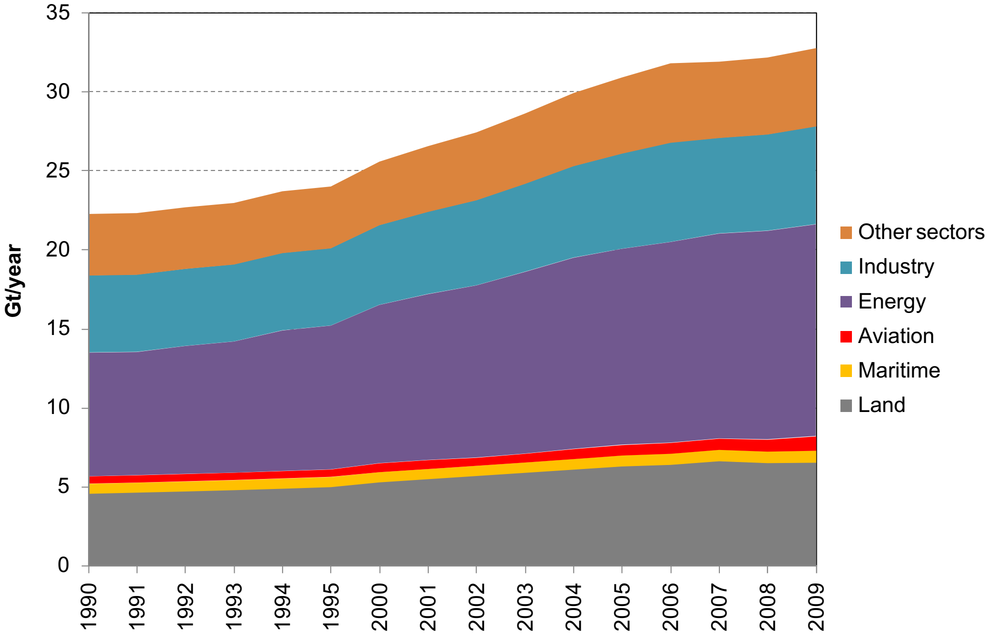

Figure 11 Worldwide energy-related CO_2 emissions of various sectors (worldwide). Source: IEA, 2011: CO_2 emissions from fuel combustion highlights. [Available on line at http://www.iea.org/co2highlights/] Assessed at 02 Feb 2012.

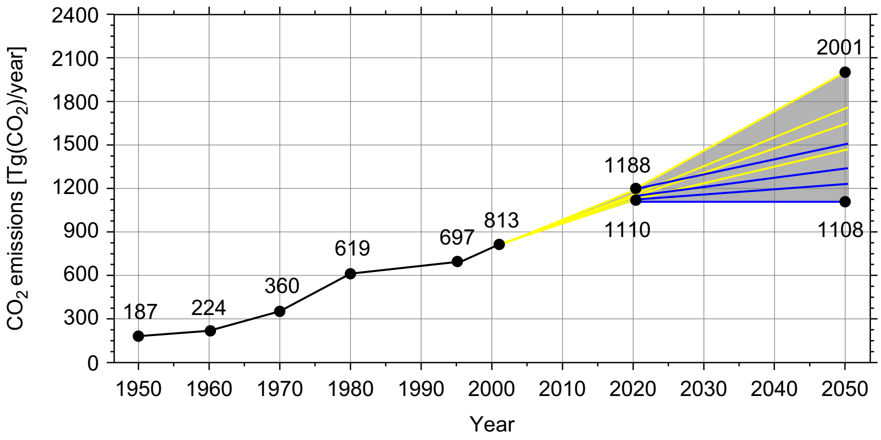

Figure 12 Possible range of future maritime CO_2 emissions. Source: Eyring, V., H. W. Köhler, A. Lauer, and B. Lemper, 2005: Emissions from international shipping: 2. Impact of future technologies on scenarios until 2050. *J. Geophys. Res.*, **110,** D17306. (See Figure 10 for further details.)

3.13.3.2.3 Air Transportation

Air transport is currently a small but nonetheless significant contributor to climate, mainly as a result of the various, interrelated effects of aircraft emissions. However, given the projected sustained rapid growth of the air transport industry of around 5% per year, aircraft emissions are expected to constitute a substantial proportion of global greenhouse gas emissions by 2050 (Bows et al. 2009). Global aviation CO_2 emissions in 2005 were estimated to be 733 Tg, which constituted roughly 2–2.5% of total anthropogenic CO_2 emissions (Lee et al. 2010). By 2050, in the worst case scenarios, those emissions are projected to have grown by a factor of three over 1992 levels (Figure 13). Under this pressure, aircraft manufacturers are constantly seeking to improve the efficiency of airplanes and engines. These efforts include improvements of existing designs, new configuration concepts, and new roles and requirements.

A further complication is the climate impact of NO_x emissions, because they cause changes in the concentration of other greenhouse gases. These changes partly offset each other, and their impacts are regional and thus not strictly additive. Overall, however, the combined impacts of the various consequences of commercial aircraft are estimated to be larger than the impacts of the CO_2 emissions alone (Schäfer et al. 2009).

Although CO_2 accounts for the majority of observed effects, human activities produce short-lived and spatially variable emissions that may also have a significant warming effect. Two substances closely associated with the transportation sector are

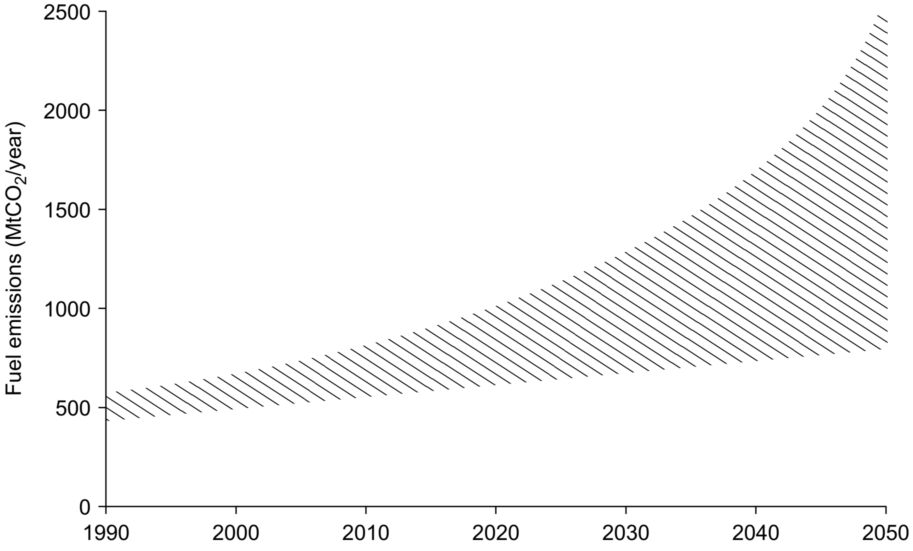

Figure 13 Global CO_2 emissions from aviation under various scenarios, 1990–2050. Source: Lee, D.S., and Coauthors, 2010: Transport impacts on atmosphere and climate: Aviation. *Atmos. Environ.*, **44,** 4678–4734.

tropospheric ozone and black carbon. Because of their short atmospheric lifetime – which ranges from weeks to months – and uncertainties about their warming potential, tropospheric ozone and black carbon are currently not included in official emissions estimates. Tropospheric ozone is estimated to have the third largest increase in radiative forcing since the preindustrial era, behind CO_2 and CH_4 (EPA 2009). It is produced when precursors such as NO_x, CO, and NMVOCs react with sunlight in the atmosphere. Motor vehicle exhaust accounts for a majority of NO_x and CO emissions, and is also the largest source of NMVOCs. Black carbon is an aerosol that causes warming by both absorbing solar radiation in the atmosphere and by reducing the reflectivity of snow and ice. The net impact of these two warming effects is estimated to be slightly lower than that of ozone, albeit with a higher degree of uncertainty. Black carbon is a component of the PM emitted from incomplete combustion processes, especially the burning of diesel fuel. Transportation is estimated to account for about one fifth of black carbon emissions (Bond et al. 2004). Unlike CO_2 emissions, ozone precursors and black carbon can be restricted by emissions controls. Both have been significantly reduced by earlier control technologies and are expected to be further reduced. Given the short lifespan of black carbon and ozone precursors, reducing their respective emissions would reduce warming within weeks to months (Unger et al. 2009).

3.13.3.3 Indirect Emissions

Indirect emissions are related to economic and industrial processes sustaining the transport system (production of fuels, vehicles and construction materials). They all have a life cycle timing their production, utilization, and disposal. Thus, the evaluation of the transport–environment link without the consideration of cycles in the environment and in the product life is likely to convey a limited overview of the situation and may even lead to incorrect appraisal and policies. At present, however, estimations have high uncertainties and should be taken into account critically. Figure 14 shows estimations for GHG emissions per passenger kilometer traveled of several vehicles. The differences of urban diesel bus estimated for two different traffic modes (peak vs. off peak) indicate the significance of the issue.

3.13.3.4 Impacts

3.13.3.4.1 On Health

The concern regarding emissions is the detrimental impact these may have on human health. We will not discuss road accidents, effects on physical activities and urban landscape, traffic congestion, and noise pollution (although their significance should be noted); instead, we will focus on the dimension for which ample evidence has been gathered through numerous studies since the late 1980s. According to WHO estimates, more than 2 million premature deaths each year are attributed to urban outdoor air pollution as well as indoor air pollution from the combustion of solid fuels. More than half of them occur in developing countries (WHO 2005). For the most part, these emissions have potential impacts on the human respiratory system, ranging from difficulty in breathing to death.

The effects of transport-related pollution on the urban scale concern air quality and health impacts due to particles, their toxic components, and toxic short-lived gases (Uherek et al. 2010). The most significant pollutant in terms of health is PM. The health effects of PM are strongly linked to particle size. Small particles, such as those from fossil fuel combustion, are likely to be most dangerous, because they can be inhaled deeply into the lungs, settling in areas where the body's natural clearance mechanisms cannot remove them. The constituents in small particulates also tend to be more chemically active and may be acidic as well and therefore more damaging (WHO 1994). Short-term increases in PM

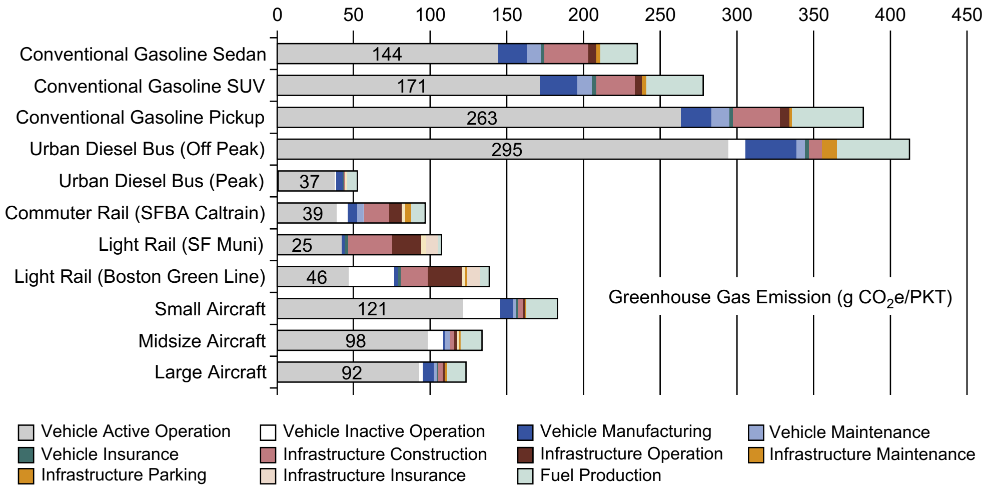

Figure 14 GHG emissions per passenger kilometer traveled (PKT) of several vehicles. Source: Chester, M.V., and A. Horvath, 2009: Environmental assessment of passenger transportation should include infrastructure and supply chains. *Environ. Res. Lett.*, **4**, (2), 1–8. Adapted from Uherek, E., and Coauthors, 2010: Transport impacts on atmosphere and climate: land transport. *Atmos. Environ.*, **44,** 4772–4816.

lead to increased mortality, increased admissions to hospital for respiratory and cardiovascular diseases, increased frequency of respiratory symptoms and use of medication by people with asthma, and reduced lung function (WHO 1994). More demonstrative and sometimes controversial evidence comes from a number of epidemiological studies which have linked short-term increases in PM levels, such as the ones that occur during pollution episodes, with immediate (within 24 h) increases in mortality. This pollution-induced spike in the death rate ranges from 2% to 8% for every 50 $\mu g\, m^{-3}$ increase in particulate levels. These basic findings have been replicated on several continents, in cities as widely divergent as Athens, Sao Paulo, Beijing, and Philadelphia (Shprentz 1996; HEI 1995; Ostro 1993). These estimates should be viewed with caution, however, because some of those who die during a pollution episode were already sick, and the pollution may have hastened the death by only a few days. The association of PM with health effects has been determined in environments with complex mixtures of highly correlated pollutants, making it difficult to disentangle individual effects. The effects attributed to PM could therefore be interpreted as indicating the effects of the pollutant mixture as a whole. The evidence on the health effects of O_3 and nitrogen dioxide (NO_2) and other pollutants resulting directly from the combustion of fossil fuels is similarly unclear. The effects may actually represent the impact of fine particles that are not usually monitored. The estimates of health impact for each pollutant should therefore take account for the complexity of the situation (Anenberg et al. 2010). Relative risks have been summarized indicating PM2.5 as the most dangerous pollutant (Figure 15). Studies conducted in Europe further emphasize this observation (Boldo et al. 2006).

3.13.3.4.2 On the Planet

At the second decade of 21st century, the world is faced with many challenges including volcanic activity, flooding, drought, fire and hurricanes. Much of the world's population is located in areas that are susceptible to flooding, while 20 of the 30 megacities of world (population greater than 10 million) are located near sea level.

The main impact of GHG emissions from the burning of fossil fuels on the planet is, as their name indicates, the 'Greenhouse Effect' that exacerbates the earth's natural greenhouse effect. The greenhouse effect is driven via infrared radiation. GHGs trap some of the infrared radiation that escapes from the earth, which makes/keeps the earth warmer than it would otherwise be. GHG act as a 'blanket' for this infrared radiation and keep the earth's lower layers of the atmosphere warmer and the upper layers cooler, than it would otherwise be if the GHGs were not there. This is accepted as a fact by almost all researchers, and serious doubting starts from this point.

A possible impact may result from the possible sea-level change. In some cases this would simply result in the inundation of low-lying areas around the world's oceans. This would not occur overnight, and there would be more than enough time for individuals in these areas to move to higher ground. On the other hand, complacency could create a disaster in the wake of sea-level surge events. These are, for example, the large

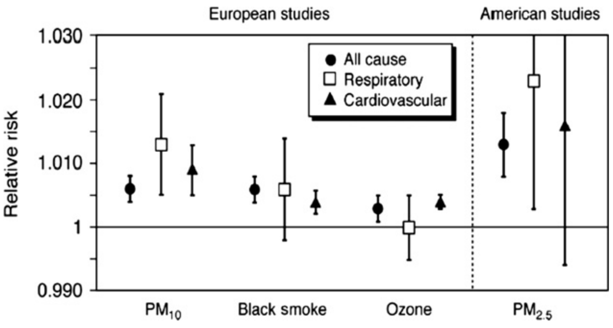

Figure 15 Summary estimates for relative risks (RR) for mortality and different air pollutants. Source: Uherek, E., and Coauthors, 2010: Transport impacts on atmosphere and climate: land transport. *Atmos. Environ.*, **44,** 4772–4816.

waves created by storms that usually come crashing ashore as part of a hurricane or typhoon.

One of the many negative outcomes to the planet is the acidification of the earth's oceans. Ocean acidification is the changing of the planet's oceans pH levels from alkaline to acid. The oceans absorb about 25% of the CO_2 emissions from the planet's atmosphere. This helps offset or mitigate possible effects on climate. When CO_2 is absorbed by the oceans, it dissolves in the seawater and carbonic acid is formed. Carbon emissions have lowered the pH of the oceans by approximately 10% since the advent of the industrial revolution. Ocean acidification decreases the ability of marine organisms such as phytoplankton and algae to function. Ocean acidification has also been linked to the dying off of coral reefs, as well as negatively impacting fish populations.

Other impacts include (Rodrigue et al. 2009):

Water quality. Transport activities have an impact on hydrological conditions. Fuel, chemical and other hazardous particulates discarded from aircraft, cars, trucks, and trains or from port and airport terminal operations, such as deicing, can contaminate rivers, lakes, wetlands, and oceans. Because demand for shipping services is increasing, marine transport emissions represent the most important segment of water quality inventory of the transportation sector. The main effects of marine transport operations on water quality predominantly arise from dredging, waste, ballast waters, and oil spills. Major oil spills from oil cargo vessel accidents are one of the most serious problems of pollution from maritime transport activities.

Soil quality. The environmental impact of transportation on soil consists of soil erosion and soil contamination. Coastal transport facilities have significant impacts on soil erosion. Soil contamination can occur through the use of toxic materials by the transport industry. Fuel and oil spills from motor vehicles are washed on road sides and enter the soil. Chemicals used for the preservation of railroad ties may enter into the soil. Hazardous materials and heavy metals have been found in areas contiguous to railroads, ports, and airports.

Biodiversity. Transportation also influences natural vegetation. The need for construction materials and the development of land-based transportation has led to deforestation. Many transport routes have required draining land, thus reducing wetland areas and driving-out water plant species. The need to maintain road and rail rights-of-way or to stabilize slopes along transport facilities has resulted in restricting growth of certain plants or has produced changes in plants with the introduction of new species different from those which originally grew in the areas. Many animal species are becoming extinct as a result of changes in their natural habitats and reduction of ranges.

In reverse, all the above will effect transportation itself. The effects derive from possible (1) temperature and precipitation changes, (2) water- and sea-level change, and (3) abatement activities (Black 2010) and include

- flooding of streets and highways and damage to transport infrastructure during storm events;
- changes to the port terminal facilities, increase of inland navigability and channelization;
- permanently frozen ground in north areas and flooding of at-grade and subway rail transit systems in metropolitan areas;
- flooding of airports located in coastal areas, airports reconstruction, and issues related to the safe and efficient operation of aircraft. Changes in wind direction and strength related to atmospheric conditions could be of concern in the future. Air temperature can impact flights if, when the temperature exceeds a certain threshold level, air density becomes too low to allow the aircraft to gain lift.

3.13.4 Mitigation Actions

Reactions against the above impacts are taking place on three levels:

1. Political–social
2. Science/technological
3. Legislation

Nevertheless, it should be remembered that the nature and extent of transportation problems vary from one country to another. Although most developed nations have taken strong action to control urban pollution, this is not the case for developing countries, wherein the concentration of wealth among the economic and political elite has distorted transport policies. A disproportionate share of funds is spent facilitating the ownership and use of private cars, while the needs of mostly low-income bus riders, pedestrians, and cyclists are ignored.

Below we focus on measures/actions taken to reduce urban air pollution and GHG emissions and on possible future pathways.

3.13.4.1 Urban Air Pollution

Although aviation (airport/near airport) air pollution may be important for local environment it is not regulated. Maritime pollution control began recently in European Union (EU) by limiting the sulfur content to 0.1% in marine fuels for harbor regions in 2010 and the United States adopted emissions standards for NO_x, CO, and HC for all US ships with engines manufactured after January 2004 and recently issued plans for new emission standards for diesel engines onboard large oceangoing vessels (Eyring et al. 2010). Hence, the discussion will focus on road transportation pollution.

In the early 1960s, where eye irritation was first reported in Los Angeles County, a typical car (without pollution control devices) emitted about $48\,\mathrm{g\,km^{-1}}$ CO, $14.5\,\mathrm{g\,km^{-1}}$ hydrocarbons (HCs), and $2.55\,\mathrm{g\,km^{-1}}\,NO_x$. After the pioneering chemistry research of A.J. Haagen-Smit and other scientists at the California Institute of Technology, it was found that NO_x and HCs exposed to sunlight produced secondary pollutants (photochemical smog) that caused eye and throat irritations and reduced visibility. Further studies indicated that the complex and various pollutants existing in automobile emissions came from four sources: engine exhaust, crankcase blowby, carburetor, and fuel tank. These investigations were central to the development of various emissions-control technologies (Krier and Ursin 1977). Since then, emissions regulations and the usage of emissions reduction technologies have evolved at different rates throughout the world. Generally, the US and western European countries have been forerunners in these areas.

In the United States, the Clean Air Act of 1970 granted the Environmental Protection Agency (EPA) authority to regulate motor vehicle pollution, and the Agency's emission control policies have become progressively more stringent since the act's inception. EPA standards dictate how much pollution vehicles may emit, but manufactures decide how to achieve compliance with the agency's standards. Emissions reductions in the early 1970s occurred primarily because of fundamental improvements in engine design, the addition of charcoal canisters to collect hydrocarbon vapors, and the installation of exhaust gas recirculation valves to reduce nitrogen oxides.

The advent of (two-way) catalytic conversion technology in 1975 significantly reduced hydrocarbon and carbon monoxide emissions. The use of catalytic converters also provided an enormous ancillary environmental benefit. Because lead contained in fuel irreversibly damages catalysts, the widespread introduction of unleaded gasoline was initiated in 1975. The subsequent elimination of lead from gasoline resulted in dramatic reductions in ambient lead levels and alleviated many lead-related environmental and human health effects.

The next major milestone in vehicle emission control technology came in 1980–81. These years witnessed the introduction of one of the most commonly used emissions systems for gasoline powered vehicles – one that falls into the exhaust gas aftertreatment category – the 'Three-Way Catalyst.' These systems convert carbon monoxide and hydrocarbon emissions into carbon dioxide and water. And they also reduce nitrogen oxides to elemental nitrogen and oxygen. Additionally, three-way catalysts employ onboard computers and oxygen sensors that help optimize systems' reduction efficiencies.

In response to increasingly stringent emissions standards, manufacturers continue to equip new cars with ever more sophisticated emission control systems. The enduring evolution of emissions reduction technology has occurred in three principle arenas: (1) engine design, (2) fuel related technologies, and (3) exhaust gas aftertreatment (DieselNet 2002).

In the arena of diesel emission reduction, DPFs and Diesel oxidation catalysis (DOCs) have gained widespread use in locations where their application is not impeded by excessively high fuel sulfur concentrations. These devices can significantly reduce the amount of diesel particulate matter that is emitted into the environment. Also, selective catalytic reduction (SCR) and lean NO_x-trap (LNT) technologies show the most promise as solutions to achieve the strict NO_x standards.

Intense international attention is now focused on efforts to reduce or eliminate sulfur from gasoline and diesel fuels as well as lubricating oil. The elimination of sulfur from diesel will facilitate the ubiquitous employment of catalytic technologies in gas and diesel applications. Because sulfur in diesel increases SO_x emissions – which are known to oxidize in catalytic devises and combine with moisture to create sulfuric acid – the elimination of sulfur will mitigate environmental consequences associated with sulfuric acid (i.e., acid rain), which causes acidification of waterways, crop damage, etc.

In the United States, vehicle emissions were subjected to further reductions by provisions of the 1990 Amendments to the Clean Air Act. The Amendment's mobile source provisions required: increased durability, improved control of evaporative emissions, and computerized diagnostic systems that identify malfunctioning emission controls (DieselNet 2004).

The EU also has control over regulation of emissions in EU member states (the European Commission's "Euro Standards"). Since the Euro 1 stage, EU regulations introduced different emission limits for diesel and petrol vehicles. Diesels have more stringent CO standards but are allowed higher NO_x emissions. Petrol-powered vehicles are exempted from PM standards through to the Euro 4 stage, but vehicles with direct injection engines will be subject to a limit of 0.005 $\mathrm{g\,km^{-1}}$ for € 5 and 6. A particulate number standard (PN) is part of € 5 and 6, but is not final. The standard is to be defined as soon as possible and at the latest upon entry into force of Euro 6 (EC 2007).

Other countries have developed their own standards, or are participating in 'cross-regional programs,' whereas some such as Brazil have chosen to adopt the standards of other nations.

The above combination of ICE and end tailpipe technology, policy making, and legislation reduced to a large extent road transportation emission of urban pollutants even while fuel use and vehicle kilometers traveled increased. As already mentioned, since the 1980s exhaust emissions of CO, NO_x, hydrocarbon, and PM from new vehicles have been reduced by about a factor of 10–100 (Krasenbrink et al. 2005).

3.13.4.2 GHG Emissions

Almost all industrialized countries use standards on new vehicles to reduce vehicle fuel consumption and CO_2 emissions. Because of various historic, cultural, and political reasons, different countries and regions have chosen to adopt different fuel economy (FE) or emission standards (ES). These standards differ in stringency, by their apparent forms and structures, and by how the vehicle FE or GHG emission levels are measured – that is, by testing methods. They also differ by implementation requirements, such as mandatory versus voluntary approaches.

The research on FE improvement potential clearly suggests that there is scope for progressively tightening standards over a longer time frame, with milestones for a 30% improvement over current levels by 2020 and around 50% improvement by 2030 or soon after. Such standards would be valuable for increasing regulatory certainty for manufacturers faced with long investment cycles, enabling them to bring new technology to market. In addition, research shows that FE mandatory standards enable greater GHG emissions reductions (on average 2–3% per year) than voluntary systems (on average 0–1% reductions per year). Regulation and standard setting is a powerful tool in reducing emissions and cleaning up transport. Regulatory certainty also facilitates the development of advanced technology. However, very few countries outside the OECD have developed fuel economy policies, standards, and regulations.

More than 75% of the world light duty market has FE, fuel consumption, or CO_2 standards. There are a range of approaches to standard setting across countries, and target rates of FE improvement may differ, but all have the same goal of promoting more efficient new cars. Standards for the world's largest markets are summarized in Table 2. GHG emissions of HFCs from air conditioning systems are included in US and EU standards, based on new technologies that provide 'off-cycle' emission reductions.

Countries concerned with energy/oil security have preferred FE or fuel consumption as a metric; in the latter case, fuel consumption ($\mathrm{l\,100\,km^{-1}}$) is preferred over fuel economy ($\mathrm{km\,l^{-1}}$). Countries focusing on climate issues have preferred CO_2 of GHG emissions as a metric (in this case the GHG standard includes air-conditioning N_2O, and CH_4 emissions).

The form of the standard varies. Almost all countries now use a corporate average instead of minimum or maximum value standards because fleet averaging offers a greater incentive to improve across models, whereas there is no incentive to improve vehicles that already comply with a value standard. In addition, fleet averaging allows greater flexibility for automakers to sell a diverse fleet of vehicles. Among fleet average standards, some countries use a single standard that the entire fleet must comply with. Other standards use an attribute of the vehicle to differentiate, with the standard varying according to either weight of the vehicle or footprint (size). Under a weight-based standard, engine downsizing improves efficiency but also reduces vehicle weight, which may also expose it to a stricter standard. The way the standard varies according to weight can be adjusted to put more or less pressure on heavier vehicles to improve fuel economy. Weight-based standards provide fewer strategy options for automakers to use technology and fleet composition shifts to comply with standards. Figure 16 summarizes the actual fuel consumption data in place and nearest targets enacted or proposed thereafter by selected countries around the world – making adjustments for differences in test cycles in different countries. The standards currently in place cover a relatively short period of time; none extending beyond 2020.

A large part of the early success in increasing fleet-average vehicle fuel economy and CO_2 emissions is due to vehicle dieselization. This trend occurred in Europe due to the inherent efficiencies of diesel engines and higher energy content of diesel. However, it has been argued that dieselization of the passenger vehicle fleet did not result in overall decrease in vehicular GHG emissions. It has been argued that there have only been marginal energy and CO_2 emission savings as a result of this large shift to diesel engines, particularly because the vehicles tend to be heavier and they tend to be driven more than gasoline vehicles because of lower diesel prices and better fuel economy (Schipper and Fulton 2008). Further analysis showed that fuel taxes must act in harmony with fuel economy policies in order to ensure the overall increase in efficiency and reduction in fuel consumption (UNDESA 2011).

Approaches in which the entire industry must meet one target contrast with the US CAFE policy, which requires each company to meet standards for cars and light trucks. EU's (and Japan's) approach is based on a more coordinated market economy perception (in which the government aims to develop consensus between powerful business actors, both via laws as well as by way of constructive discourse), versus a sense that fuel economy regulations is an unwelcome market intervention. It seems to work better in improving the fuel efficiency and CO_2 emissions of new vehicles sold – skewed, however, by the human tendency to consume more.

3.13.5 The State of Things and the Future Potential

Before any discussion concerning the future potential of energy – transportation relation, it is useful to keep in mind the characteristics of unsustainable and sustainable transport (Table 3).

Obviously, the current transportation system is unsustainable. So, the question is: 'Should we expect to ever achieve a sustainable transportation system?' Some commentators believe this is an unattainable goal. In the case of 'sustainable development,' Glasby (2002) argues for a totally new paradigm because, in his view, the world is embarked on a course that is manifestly unsustainable. That may be so in the case of sustainable development, but that doesn't mean that we can't develop a transportation system that is more sustainable than the one that currently exists.

Table 2 Fuel economy and GHG standards for vehicles around the world

Country/region	*Metric*	*Structure*	*Test method*[a]	*Programme details*[b]	*Implementation*
European Union	CO_2 emissions ($\mathrm{g\,km^{-1}}$)	Overall light-duty fleet	EU NEDC	40% Reduction MY 2008–20	Voluntary
USA	FE (mpg) and GHG equivalent ($\mathrm{g\,CO_2eq\,mi^{-1}}$)	Cars & light trucks	US FTP 75	20% Reduction MY 2011–16	Mandatory
Japan	FE ($\mathrm{km\,l^{-1}}$)	Weight-based	Japan JC08	19% Reduction MY 2010–15	Mandatory
China	Fuel consumption ($\mathrm{l\,100\,km^{-1}}$)	Weight-based	EU NEDC	12% Reduction MY 2008–15	Mandatory
Canada	GHG equivalent ($\mathrm{g\,CO_2eq\,mi^{-1}}$)	Cars & light trucks	US FTP	20% Reduction MY 2011–16	Voluntary
Australia	Fuel consumption ($\mathrm{l\,100\,km^{-1}}$)	Overall light-duty fleet	EU NEDC	10% Reduction MY 2004–10	Voluntary
Taiwan/South Corea	FE ($\mathrm{km\,l^{-1}}$) and CO_2 emissions ($\mathrm{g\,km^{-1}}$)	Engine size	US FTP	13% Reduction MY 2012–15	Mandatory

[a] *Refers to applied emission test cycles: New European Driving Cycle (NEDC), Federal Test Procedure (FTP 75), and Japanese Cycle (JC08).*

[b] *Refers to reduction in CO_2 per distance emissions.*

Source: United Nations Department of Economic and Social Affairs (UNDESA), An, F., R. Earley, and L. Green-Weiskel, 2011: Global overview on fuel efficiency and motor vehicle emissions standards. Policy options and perspective for international cooperation. Background Paper No.3, CSD19/2011/BP3.

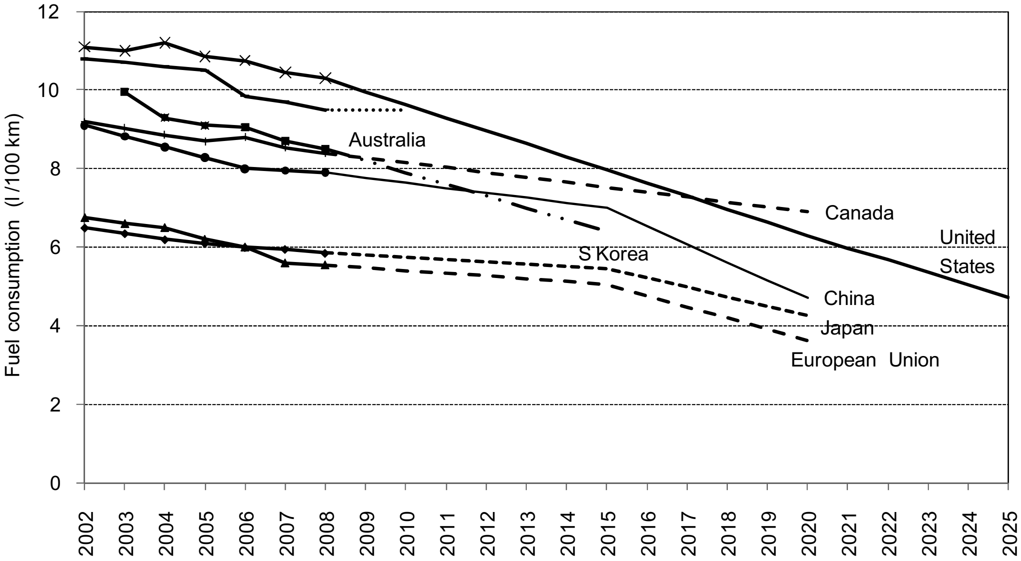

Figure 16 Actual fleet average fuel consumption data through 2008 and nearest targets enacted or proposed thereafter by region. Sources: An, F and A. Sauer, 2004: Comparison of passenger vehicle fuel economy and GHG emission standard around the world. Prepared for the Pew Center on Global Climate Change. [Available on line at http://www.c2es.org/docUploads/Fuel%20Economy%20and%20GHG%20Standards_010605_110719.pdf] Assessed at 02/02/2012; United Nations Department of Economic and Social Affairs (UNDESA), An, F., R. Earley, and L. Green-Weiskel, 2011: Global overview on fuel efficiency and motor vehicle emissions standards. Policy options and perspective for international cooperation. Background Paper No.3, CSD19/2011/BP3; Center for Climate and Energy Solutions (C2ES), 2012: Comparison of actual and projected fuel economy for new passenger vehicles. [Available on line at http://www.c2es.org/federal/executive/vehicle-standards/fuel-economy-comparison] Assessed at 02 Feb 2012.

Table 3 Key characteristics of unsustainable and sustainable transportation

	Unsustainable transport	*Sustainable transport*
Transportation volume	Requires a high level of numbers of trips and trip distances, because of sprawled urban development and inefficient logistical networks	The demand for travel is minimized and journeys are short, because of compact urban development, mixed land use, and optimized logistical chains
Transportation modes	Reliance on private motorized transport for passengers, and heavy goods vehicles for freight	Most passenger trips are made by public or nonmotorized transport, and freight is carried by rail and other low-carbon modes
Transportation technologies	Vehicles rely on inefficient, fossil-fuel engines	Low carbon vehicle technologies are mainstreamed, including highly efficient engines, hybrids, plug-in hybrids and electric vehicles
	The transport network is inefficiently managed	New technologies such as 'Intelligent Transport Systems' and 'Smart Logistics' help manage transport systems in highly efficient ways.
Transportation pricing	The price paid by users for vehicles, fuel, parking, and road space do not cover the full external costs to society, encouraging motorized vehicle use at the expense of more sustainable choices	The price paid by transport users fully 'internalizes' the true costs, managing growth in motorized vehicle use and encouraging environmentally friendly alternatives
Resilience to climate	Transport systems are highly vulnerable to the climate	Transport assets are screened against vulnerability criteria, and are developed in a way that is resilient toward possible changes in climate

Sources: Kennedy, C., E. Miller, A. Shalaby, H. Maclean, J. Coleman, 2005: The four pillars of sustainable urban transportation. *Transp. Rev.*, **25**, 4, 393–414; Ruprecht, D., 2011: Transportation modes for a sustainable suburban future: overview, evaluation and suitability for testing in the project NAMO. Master Thesis, *Nat. Soc. Sci. Interface.*

Focusing on road transportation, any discussion on the future potential has to be based in the complex shown in Figure 17. The importance of each component depends on the application but the general scheme is the same (Schulte and Wirth, Undated; ACEA 2011). Because space is limited for a full discussion of this complex, we only briefly comment on energy and environmental issues in conjunction with some customer expectations.

Regarding customer expectations, trends are very similar for gasoline and diesel engines, especially in the volume segments and markets. Customers are very focused on total cost of ownership, which is determined by such factors as price, resale value, fuel consumption (and fuel price), maintenance cost, as well as reliability, safety, and durability. At the same time, customer expectations regarding 'fun to drive' are still increasing. This translates into a continuation of the 'power and

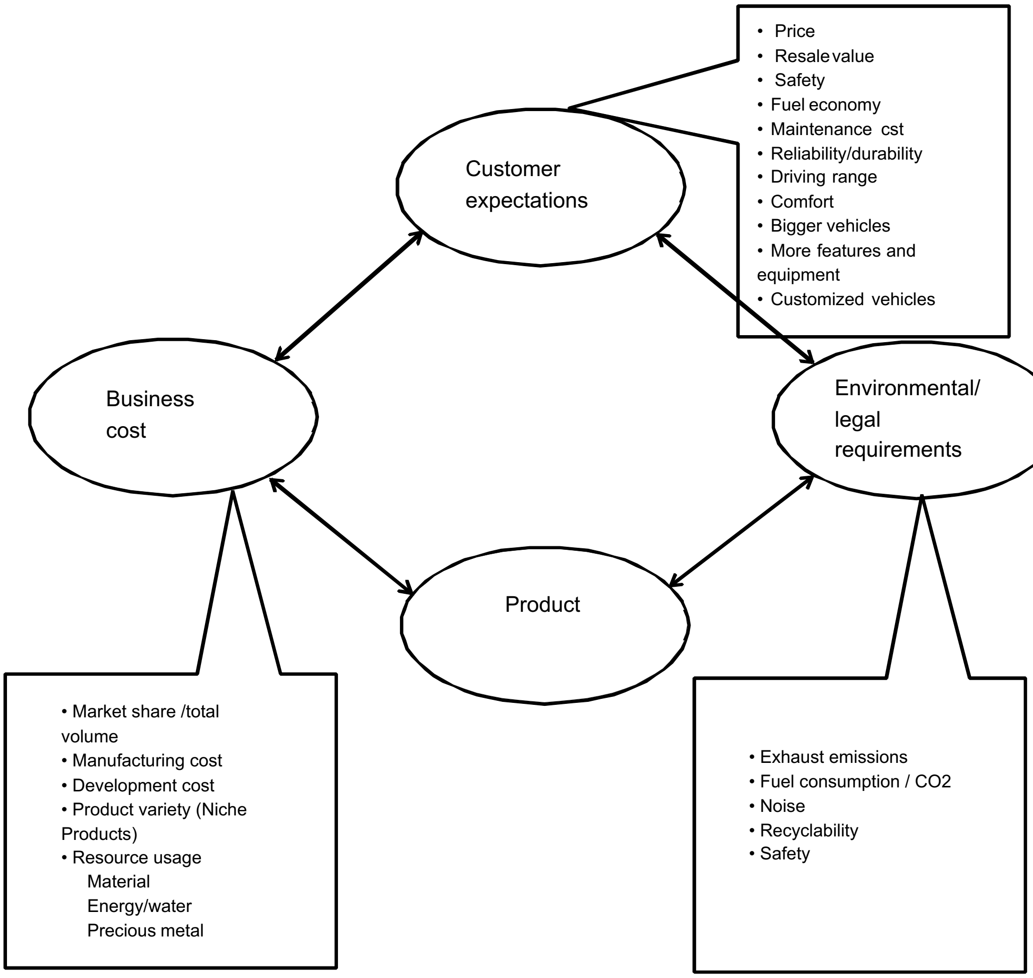
• Price
• Resalevalue
• Safety
• Fuel economy
• Maintenance cst
• Reliability/durability
• Driving range
• Comfort
• Bigger vehicles
• More features and equipment
• Customized vehicles
Customer expectations
Business cost
Environmental/ legal requirements
Product
• Market share /total volume
• Manufacturing cost
• Development cost
• Product variety (Niche Products)
• Resource usage
Material
Energy/water
Precious metal
• Exhaust emissions
• Fuel consumption / CO2
• Noise
• Recyclability
• Safety

Figure 17 Interaction among customer expectations, environmental/legal requirements, and business aspects. Source: Schulte, H., M. Wirth, 2010: Internal combustion engines for the future. [Available on line at http://essaysforstudent.com/print.html?essay=77790.] Assessed at 12 Feb 2012.

torque race' to further improve vehicle performance and drivability. In addition to performance improvements, at steadily rising fuel prices, customers are expecting further improvements in fuel economy.

Gasoline engine technology is currently entering a new phase of intense development and technology deployment based on two major drivers: On one hand the further intensified pressure for fuel economy improvement, which has got another acceleration by recent fuel price increases, leaving the customer in an unprecedented uncertainty in terms of energy supply resulting in much more cautious purchase decisions regarding vehicle size and powertrain technology. On the other hand, drivability refinement and torque characteristics are powertrain attributes that are meanwhile positively associated primarily with modern diesel engines and therefore the gasoline engine is endangered to lose its classical footprint as being the more refined engine for the demanding customer. It is meanwhile widely accepted (Wirth and Schulte 2006) that engine downsizing in combination with pressure charging (primarily turbocharging) is the most appropriate technology bundle to address the two key challenges mentioned above at the same time. It also has been discussed in depth that direct injection is a technology with high synergy potential to further enhance the merits of turbocharging.

The available technology options for CO_2 reduction can be divided into three groups (Wirth and Schulte 2006):

- Aggressive friction reduction (including options like on-demand water pump, offset crank, variable oil pump) and thermal management (including options like split cooling and heat storage), as well as high compression ratio enabled by homogeneous direct injection.
- Downsizing, including a change of the engine architecture to the next smaller engine family plus turbocharging.
- Stratified part-load operation with key enabler the spray guided stratified combustion system, with its best possible fuel economy improvement versus homogeneous operation.

Further, meeting even higher levels of pollutant emissions controls will require aftertreatment technological advances. Catalysts with lower thermal mass and light-off temperature that can be coupled to the exhaust manifold will be required. Catalysts are needed to very efficiently adsorb emissions during cold-start operations. Sophisticated models of energy operation, including predicting emissions when going from transient cold-start to full-throttle operation, coupled with a catalyst aftertreatment operating mode that can deliver precise individual-cylinder air/fuel control must be developed.

Today, along with gasoline and Diesel, engines that use more than one fuel are on the market and an increasing future demand is assumed for alternative fuels and particularly CO_2-neutral fuels. The current and short-term fuel mixture includes:

Fossil fuels. Second to oil, natural gas (NG) is the most commonly used fossil fuel in transportation. NG is likely to become the most significant energy product throughout the next 30 years (Bilgin 2009). Diesel can also be generated synthetically via the Fischer–Tropsch process from natural gas.

Biofuels. Bioethanol and biodiesel, the former using fermentable plant material to produce combustible ethyl-alcohol, and the latter using plant and even animal oils to produce combustible fuels via transesterification. The global annual production of biofuels increased 17% in 2010 to reach an all-time high of 105 billion liters up from 90 billion liters in 2009. At the end of first decade, ethanol global production was more than three times that of 2000 and biodiesel production more than ten times (IEA 2012). Currently, biofuels provided 2.7% of all global fuel for road transportation – an increase from 2% in 2009. Current biofuels production technologies use established arable crops and feedstock cost is a major element of the biofuel production economics because prices of these established crop feedstocks are volatile. There is a threshold above which biofuel cannot produced without threatening food supplies and biodiversity. Second-generation biofuels production (produced sustainably by using biomass consisting of the residual nonfood parts of current crops), when stabilized, is expected to surpass these problems.

Electric and hybrid electric vehicles. Electric vehicles offer a number of advantages, such as low noise levels and virtually no toxic emissions during operation. Emissions occur elsewhere, however, during the production of the batteries and the electricity needed to recharge them. Still, extensive use of such vehicles has been inhibited by the current limitations of battery technology, such as limited driving range, and by high costs, restricting their use to special niche applications. A breakthrough for battery-powered vehicles seems unlikely in the near future, even though batteries are constantly becoming cheaper and more efficient. It would be better if the electricity were produced aboard the vehicle, which is one of the reasons why many automakers appear to be focusing instead on hybrid electric vehicles or on fuel cells. Hybrid electric vehicles combine the ICE of a conventional vehicle with the battery and electric motor of an electric vehicle. A further development is the introduction of plug-in hybrids, that is, full hybrids that can be recharged both by the vehicle driving cycle and by external sources. A hybrid is more expensive and heavier than the corresponding conventional vehicle, but might cut fuel consumption and toxic emissions by about half in urban driving. GHG emissions may well be reduced compared with an equivalently sized ICE vehicle, but total emissions will depend on CO_2eq intensity of the electricity drawn from the grid.

Fuel cells. With the use of hydrogen fuel cells, hydrogen is converted via electrochemical means into electrical energy to power a motor. This results in zero emissions at source, thereby ensuring considerable health and environmental benefits, as well as reduced noise. City buses, because of relatively lower barriers, might be among the first fuel cell-equipped vehicles used on a larger scale. Building a general hydrogen infrastructure would take a long time and involve substantial costs. The introduction of fuel cells for vehicles would be facilitated by the use of a liquid fuel instead of hydrogen gas, because the infrastructure for liquids is mostly in place, and some fuel cells already utilize liquid fuels directly.

Using projections based on the this fuel mixture and technological advances on the ideal cases of appropriate timing of air pollutant emission regulation implementation in developing countries and investment in reducing the sulfur content of petroleum products for road transport to or below 10 ppm in all countries, road sector emissions would approach zero in 2050 (Takeshita 2011) (**Figure 7**). In the case of urban pollutants and despite the differences in the fuel mixture scenarios, the potential for further reduction is clearly indicated.

Projections of CO_2 emissions are more uncertain. In effect, results basically depend on the fuel mixture assumptions. Estimations for scenarios ranging from no CO_2 mitigation policies (Business-as-Usual Scenario) to CO_2 mitigation policies combined with optimistic cost assumptions – the specific costs of the components of hybrid vehicles, electric vehicles, and fuel cell vehicles not included in baseline gasoline or diesel ICEs are assumed to reach levels that are 50% lower than their reference specific costs. (**Figure 18**) shows that reduction is possible only in cases of CO_2 mitigation policies with optimistic cost assumptions. The best result demands that the share of hybrids, especially plug-in hybrids, is almost 100% of the global fleet (light-duty vehicles, buses, and medium-duty trucks) in 2050. In this case, global road fuel consumption in 2050 decreases by about 28% compared with the Business-as-Usual scenario, and road transport accounts for 16% of the total global CO_2 emissions reduction in the same year. This requires lowering of the specific cost of batteries for the penetration of plug-in hybrids. This scenario indicates further that the increasing penetration of hybrids leads to the reduction in the number of road vehicles fueled by biomass-derived FT synfuels under the CO_2 emission constraints. These results show that except for electric two-wheelers, pure electric vehicles and fuel cell vehicles are transport technologies that might play a role in the second half of the century and/or in a more carbon-constrained world, a demand which is equivalent to an energy paradigm change.

This is clearly indicated in **Figure 19**, which shows the CO_2 abatement measures potential (well-to-wheel emissions, from 2006 (base year) to 2030) of passenger cars in comparison with a no-action baseline and in **Figure 20**, which shows the potential development paths for the automotive sector. The three abatement paths represent different approaches to improving the carbon efficiency of passenger cars (McKinsey & Company, 2009a): (1) hybrid and electric, (2) mixture of hybrid, electric, and ICEs (mixed technology), and (3) optimized ICEs. The paths differ in the rate and time over which particular technologies penetrate the global vehicle fleet, leading to different penetration levels in 2030. The scenarios assume an aggressive reduction in the carbon intensity of electricity generation and share the same assumptions for

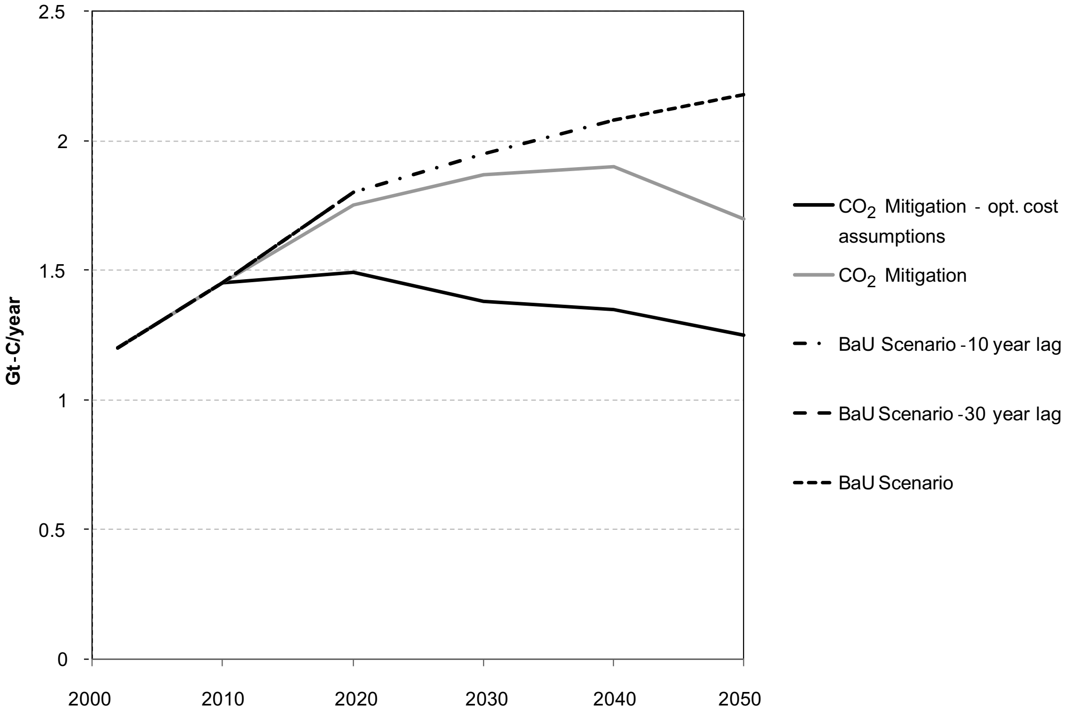

Figure 18 Global emissions of CO_2 from road vehicles for five scenarios: Business-as-Usual (BaU) scenario, the CO_2 mitigation scenario, the BaU scenario with a 10- or 30-year lag (refers to developing regions) and the CO_2 mitigation scenario with optimistic cost assumptions. Source: Takeshita, T., 2011: Global scenarios of air pollutant emissions from road transport through to 2050. *Int. J. Environ. Res. Pub. Health*, **8,** 3032–3062.

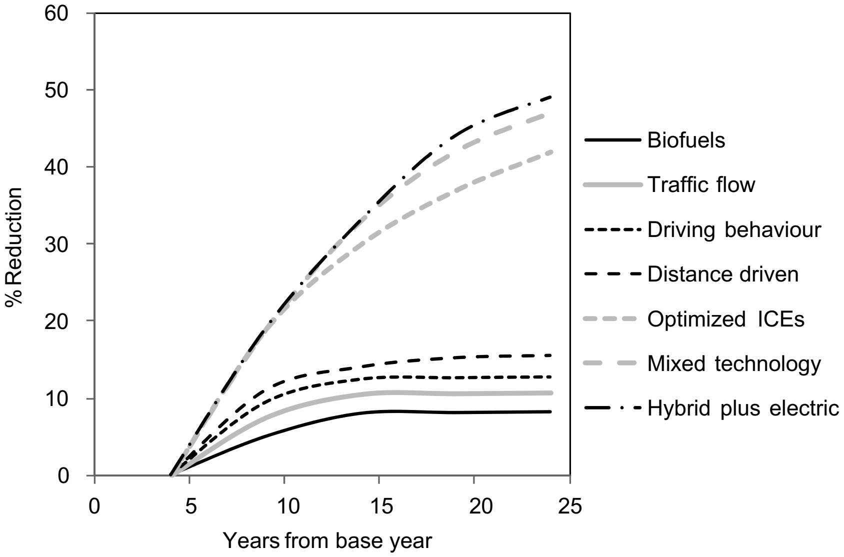

Figure 19 Global passenger vehicle CO_2 emissions abatement potential (base year: 2006). Emissions reductions for biofuels, traffic flow, driving behavior, and distance driven are based on mixed technology scenario. Source: McKinsey & Company, 2009a: Roads toward a low carbon future. Reducing CO_2 emissions from passenger vehicles in the global road transportation system. [Available on line at http://documents.eu-japan.eu/seminars/europe/other/co2_reduction/dinkel_report.pdf.] Assessed at 15 Feb 2012.

abatement using other measures (biofuels, traffic flow, shift to public transportation, ecodriving).

As shown in Figure 19, the hybrid and electric scenario gives a 49% reduction relative to the no-action emissions baseline and a 22% reduction relative to 2006 emissions levels. This represents an aggressive scenario assuming a rapid transition toward electricity-based propulsion systems and infrastructure in place to support them. All remaining ICE systems would be optimized for 130 g $CO_2\,km^{-1}$ in 2030 (well-to-wheel emissions). Mixed-technology scenario gives a 47% reduction

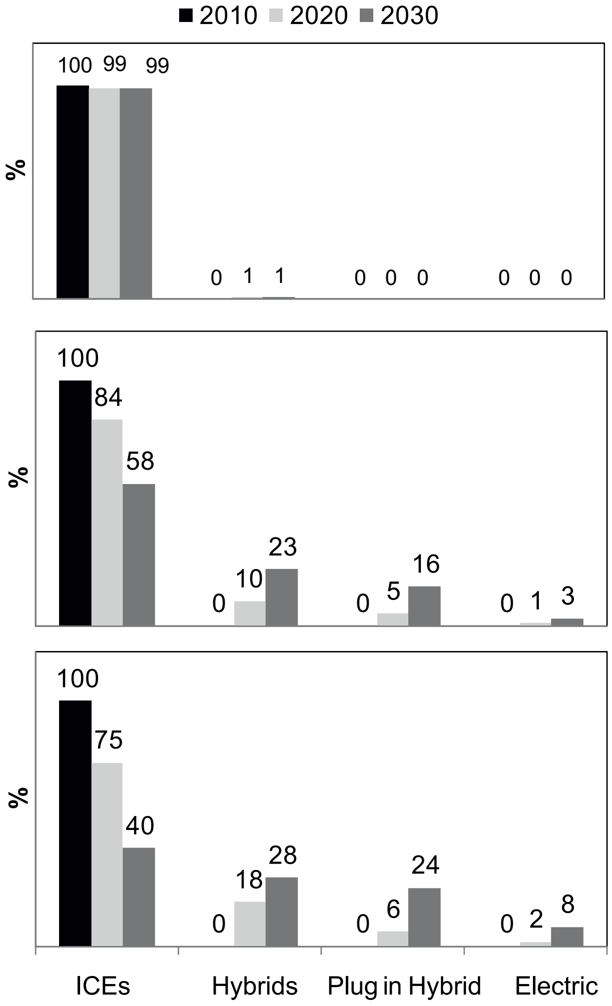

Figure 20 Potential development paths for the automotive sector. Percentages refer to vehicle fleet share. Source: McKinsey & Company, 2009b: Pathway to a low carbon economy. Version 2 of the global greenhouse gas abatement cost curve. [Available on line at http://www.mckinsey.com/Client_Service/Sustainability/Latest_thinking/Pathways_to_a_low_carbon_economy.] Assessed at 15 Feb 2012.

relative to the no-action emissions baseline and an 18% reduction relative to 2006 emissions levels. ICE systems would be optimized for 150 $\mathrm{g\,CO_2\,km^{-1}}$ in 2030 (well-to-wheel emissions). Emissions reductions for biofuels, traffic flow, driving behavior, and distance driven shown in Figure 19 are based on this scenario. ICE scenario gives a 42% reduction relative to the no-action emissions baseline and an 11% reduction relative to 2006 emissions levels. ICE systems would be optimized for 170 $\mathrm{g\,CO_2\,km^{-1}}$ in 2030 (well-to-wheel emissions). Similar results are produced for medium and heavy duty vehicles as well (McKinsey & Company, 2009b).

3.13.6 Conclusions

In identifying the essential components of energy and transportation relationship some specific features were revealed.

First, because of the combination of scarcity in cheap oil, increased global energy demand, and greater supply disruptions provoked by geopolitical dependence of Europe, fuel prices will continue to rise in the medium and long term. Indeed, mostly due to the emerging economies in Asia (in particular China and India), energy demand is rising significantly more than oil production and oil refining capacity, making disruptions in energy supply a major and increasing concern. The share of worldwide energy demand and energy market stress that these markets bring along with their expansion is overwhelming. The growth of mobility and transport systems in most emerging economies has progressed at a different speed – India and China had a slow start but have now surpassed Western regions in their economic growth rates, which is directly reflected in their transport demand, mobility growth, and increased energy demand.

Second, the green message – uses less energy – is not going to solve the problem unless economic growth stops at the same time. If it does not, any efficiency saving will soon be eaten up by higher consumption per head. Technology development policies making vehicles more energy efficient or promoting alternative propulsion systems are successful in reducing fuel consumption per kilometer, but tend to result in longer distances traveled by both passengers and freight.

Third, exponential urban expansion in developing countries is one of the major environmental challenges of this century. Current trends in urban developments are a reason for concern in terms of climate, because they are allowing private cars to gain predominance over public transport or nonmotorized travel. No matter if the mode share of automobiles is low, as in emerging economies, or very high, as in the developed world, the trend is clear: people are buying more cars every day and once they have them, they use them. Consequently, the energy use and greenhouse gas emissions from urban passenger transportation are continuing to increase.

Fourth, as a consequence of the trends just mentioned, and despite the technological progress in automobile toxic emissions, air pollution is and will continue to be a health issue in the megacities of the developing world, mainly due to the existence of old and malfunctioning vehicles.

Fifth, rail is several times more energy efficient than road shipping and aviation, emits significantly less emissions, and has the potential to improve further.

Sixth, oceangoing shipping and resulting emissions produce significant impact on atmospheric composition and climate. Control of NO_x, SO_2, and PM emissions from ships will have beneficial impacts on air quality, acidification and eutrophication, whereas CO_2 reductions will be beneficial in the general effort to reduce these emissions.

Seventh, the growth of air transport is a crucial dimension of the overall environmental impact of aviation. The latter therefore requires interpretation in the context of the rapid growth of aviation and most of its emissions.

Eighth, our ability to monitor and understand the atmosphere has taken a quantum leap in recent years. We have gone beyond naïve linear models and now appreciate that if complex systems such as the atmosphere, the oceans, and land ecosystems change, they may become unstable and more unfriendly.

Ninth and last, the share of world transportation energy use attributed to petroleum-based liquids does not change significantly over the projection period, but oil's dominance may begin to be challenged by advancing technologies. Uncertainty about the security of oil supplies, the prospect of rising oil prices, and environmental concerns about emissions associated with the combustion of petroleum pose challenges to countries that are experiencing rapid motorization and have to import large portions of their transportation fuel supplies. As a result, future trends in transportation demand will be influenced by government policies directed at reducing emissions and congestion while promoting alternative fuels, advanced vehicle technologies, and mass public transportation.

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3.14 Energy Production, Conversion, Transmission and Distribution, Policy, Planning, and Mitigation Processes – General Considerations: Large Energy Projects, Efficiency, and Vulnerability

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3.14.1 Introduction

Anthropogenic climate change has been an increasingly interesting issue of research during the last decades, primarily aiming at the identification of future-related threats and possible ways of alleviating the related harmful effects. Since anthropogenic climate change was acknowledged by the academic society, policies to combat climate change have partly been included in the decision-making agenda. Following the Stern review (2007), which recognized early action for decreasing greenhouse gas emissions as the most cost-efficient path for a successful climate policy, numerous policies have been introduced that aim at the mitigation of greenhouse gas emissions. One leading example is the launch of the Energy Package for 2020 (http://ec.europa.eu/clima/policies/package/index_en.htm) by the European Commission which identifies the crucial role of the energy sector in taking action against climate variability. Nowadays, climate policy has already been incorporated in energy policy formulation, and the attempt to internalize the external societal costs of emissions has proved crucial for the formation of the future energy mix of the world.

While a low-carbon power generation system and an overall 'greener' energy mix have been set as a priority in decision making, measures to adapt to a changing global environment have not gained much attention. Academic research on the vulnerability of the energy sector to climate variability has been limited so far and thus has not facilitated a thorough understanding of the impacts of climate variability to energy systems. Moreover, the location-specific impacts of climate variability in combination with the different energy mix of each location make the assessment of climate variability effects and of possible adaptation measures extremely case-specific and difficult to generalize. The prevailing uncertainty related to timing and intensity of climatic effects complicates the proper incorporation of adaptation parameters in future energy planning.

Energy infrastructure in most regions of the world is soon to be reinforced, replanned, and rebuilt owing to increasing demand from developing countries and decreasing lifespan or revised environmental regulations in developed countries, thus bringing a period of large investment plants in the energy sector. Climate vulnerability should be appropriately considered at all levels of energy infrastructure planning, especially because of the very long lifetime (40–80 years) of energy systems. An attempt is made in this chapter to specify the impacts of climate variability on large energy projects and propose possible climate-proof solutions for future energy projects.

In this chapter, a brief review on the impacts of climatic variability on different forms of energy supply is given in order for the reader to understand the context in which large energy projects are under climate-related risks. The analysis then focuses on thermal power plants and in particular on nuclear plants and concentrated solar thermal plants, because both technologies are integrated only in a centralized and large-scale manner. An attempt is also made to provide a number of concrete adaptation measures and proposals to policy makers. The scope of this analysis is to raise awareness and provide some insights with regard to the vulnerability to climate change of large, centralized power plants; consequently, energy security can be enhanced along with prioritization of optimum win–win mitigation and adaptation plans.

3.14.2 Vulnerability to Climate Variability

As mentioned, there is still a high level of uncertainty as regards the various aspects of climate variability and the intensity of the related effects, while the future pace of climatic change shows the highest uncertainty levels. This article will be based on robust scientific and empirical climatic evidence that has been observed currently or is expected in the future. In brief, the main observed anthropogenic climate change according to the IPPC (http://www.ipcc.ch/) 2007 report includes the following:

1. An increase of the global average temperature and an increased rate of warming.
2. Snow, ice, and frozen ground are affected by increase melting, instability of permafrost, and reduced tropical glaciers.

http://dx.doi.org/10.1016/B978-0-12-384703-4.00323-3

3. Increased or decreased runoff according to the location.
4. Increased frequency of extreme events.
5. More frequent heat waves, less cold days and nights.
6. More frequent heavy precipitation events possibly leading to floods.
7. More frequent intense cyclone activity.
8. Sea level has risen an average of 18 cm since the nineteenth century.

Projections for expected future climate variability are based on the above-mentioned observations and greatly depend on the time scale under analysis. Projected changes in surface temperature, wind patterns, solar radiation, sea level, permafrost, and rainfall along with extreme weather events are expected to occur depending on time and space. Certain weather variables of the long-term future climate projections deviate less than others; for example, average temperatures are more robust than the expected levels of precipitation.

Anthropogenic climate change as described will affect all aspects of biological, economic, and social life. Assessment of the vulnerability of different sectors, countries, and societies to climate change is necessary in order to prepare against the identified threats. Science is expected to play a vital role in the conceptualization of a sustainable future, both by means of prevention (i.e., mitigation of greenhouse gases and other forms of pollution) and by means of adaptation to the changing conditions. The energy sector is expected to be widely affected by climate variability. At the same time, energy systems are considered central to mitigation policies and thus particular attention must be given to the synergies of mitigation and adaptation measures.

Ebinger and Vergana (2011) in their report for the World Bank publications on the climate impacts on energy systems summarize all major impacts on energy resources and energy supply in **Table 1**. All different sources of energy are affected by climate variability at different levels of intensity. Large energy projects, namely large-scale installations of any form of energy supply, are the dominant feature of current energy systems. Climate vulnerability poses an additional factor of uncertainty which may increase investment costs, if impacts are assessed during the planning of the system, or increase operation costs, if no strategic adaptation measures are taken.

Large energy projects generally constitute a significant factor of climate vulnerability for their respective energy systems. Centralized energy systems, that is, systems that feature large energy projects with central dispatching and no geographical dispersion, are found more susceptible to threats of climate variability because of the limited range of diversification and an inability of efficient adjustment. Additionally, energy systems are usually designed for relatively stable weather conditions and planners rarely take into account probable weather extremes. However, central planning and large-scale installations enable proper risk management and economies of scale with regard to the cost of adaptation measures. The parameters affecting the vulnerability of different types of large energy projects should be appropriately assessed. This assessment will facilitate the achievement of long-term energy security goals that are a prerequisite for economic activities and social welfare.

3.14.2.1 Vulnerability of Energy Sector

Recent research on the vulnerability of the energy sector to climate variability categorizes the impacts in two broad categories, namely impacts on resource endowments and impacts on energy supply. Impacts on factor endowments refer to increased fluctuations of energy inputs and unusual disturbances on supply of primary energy sources. Impacts on energy supply refer to vulnerabilities and inefficiencies of the transformation sector and in particular on the technologies that convert primary energy sources to energy services. Large energy projects are a central part of today's energy systems and are found to be particularly vulnerable as compared with smaller and decentralized projects.

3.14.2.2 Vulnerability of Large Energy Projects

3.14.2.2.1 Thermal Power Plants

Extreme weather conditions have been detrimental to the operation of thermal power plants in the past. For example, in the heat waves of 2003, 2006, and 2009 in Europe some nuclear plants had to cut output, triggering fears of blackouts. In 2003, the heat wave in France caused the cut of 4000 MW because of a forced reduction in capacity and/or the turning off of 17 nuclear reactors (IHT 2007). In 2006, the European heat wave caused disruption to the power systems of France, Spain, and Germany because nuclear plants had to cut output or were given special exemption licenses to discharge water above the permitted temperature into the rivers. In 2009, France again had to cut power and import electricity from the United Kingdom similar to 2003 (UCTE 2004). The economic implications of the described failure to adapt to the changing environment were significant, because power utilities had to purchase electricity from the power market in order to meet their contract obligations at prices even 10 times higher than the average seasonal price.

In the following paragraphs, a description of the factors of vulnerability of thermal plants is given.

Water Requirements for Cooling Purposes

Thermoelectric generation requires large amounts of water for its operation. Water is required mainly for cooling purposes but also for water loss in boiler operation, flue gas desulfurization, and ash handling systems. According to statistics (Eureau 2009), it is estimated that 43% of water demand in Europe comes from cooling requirements in power plants. For specific European countries, the share of water demand for cooling in electricity production is even higher, for example in Hungary and Poland where the respective shares are 91 and 71%. As a result of the significant water dependence, considerations are already being made during the planning procedure of new power plants, for example the rejected permission of a new power plant in Arizona because of concerns about water withdrawal from the local aquifer, as noted in the USCCSP report (USCCSP 2008).

In the USCCSP 2007 report, it is estimated that around 94.6 l of water are required for the production of each kilowatt hour by a steam cycle process. Feeley et al. (2008) provide a thorough description of freshwater withdrawal and consumption factors for different power technologies, indicating

Table 1

	Relevant climate impacts			
Item	*General*	*Specific*	*Additional*	*Impacts on the energy sector*
Climate change impacts on resource endowment				
Hydropower	Runoff	Quantity (+/−) Seasonal flows high and low flows Extreme events	Erosion Siltation	Reduced firm energy Increased variability Increased uncertainty
Wind power	Wind field characteristics, changes in wind resource	Changes in density, wind speed Increased wind variability	Changes in vegetation (might change roughness and available wind)	Increased uncertainty
Biofuels	Crop response to climate change	Crop yield Agro-ecological zones shift	Pests Water demand Drought, frost, fires, storms	Increased uncertainty Increased frequency of extreme events
Solar power	Atmospheric transmissivity	Water content Cloudiness Cloud characteristics		Positive or negative impacts
Wave and tidal energy	Ocean climate	Wind field characteristics No effect on tides	Strong nonlinearity between wind speed and wave power	Increased uncertainty Increased frequency of extreme events
Climate change impacts on energy supply				
Hydropower	Water availability and seasonality	Water resource variability Increased uncertainty of expected energy output	Impact on the grid Wasting excessive generation Extreme events	Increased uncertainty Revision of system reliability Revision of transmission needs
Wind power	Alteration in wind speed frequency distribution	Increased uncertainty of energy output	Short life span reduces risk associated with climate change Extreme events	Increased uncertainty on energy output
Biofuels	Reduced transformation efficiency	High temperatures reduced thermal generation efficiency	Extreme events	Reduced energy generated Increased uncertainty
Solar power	Reduced solar cell efficiency	Solar cell efficiency reduced by higher temperatures	Extreme events	Reduced energy generated Increased uncertainty
Thermal power plants	Generation cycle efficiency Cooling water availability	Reduced efficiency Increased water needs, for example during heat waves	Extreme events	Reduced energy generated Increased uncertainty

the significance of the choice of power technology type and also the diversification of plants as regards the actual consumption of water in relation to withdrawal. According to Feeley et al. (2008), values of withdrawal for US power plants range from 0.004 gal kWh^{-1} for air-cooled natural gas combined-cycle plants to 27.113 gal kWh^{-1} for coal plants with once-through cooling systems. As regards actual water consumption, factor values range from 0.002 gal kWh^{-1} for natural gas combined-cycle plants with once-through cooling system to 0.804 gal kWh^{-1} for coal plants with a cooling pond.

Nuclear plants require substantially more water to cool or condense the coolant that is used to cool the reactor core by transferring heat from the core to the turbines. For example, a nuclear plant may require 2 billion cubic meters of water each year for cooling purposes. As a result, many scientists emphasize the contradiction between the positive role of nuclear energy in climate change mitigation efforts and the significant impacts of climate change to the operation of nuclear plants. By building new nuclear power plants to avoid an increase of greenhouse gas emissions, the energy system could become more vulnerable to increased ambient and water temperatures or even to extreme weather events like floods (e.g., the Fukushima accident in Japan was exacerbated by the floods in the installations caused by the tsunami). Because a certain level of anthropogenic climatic changes cannot be avoided, decision makers and future investors should consider this aspect of nuclear energy.

The type of cooling technology of the power plant is an important factor for its water requirements and hence its vulnerability to climate changes. Three main types of cooling technologies can be found in most power plants, namely once-through cooling technology, once-through cooling with cooling tower, and closed circuit cooling. These can be seen in the figure by Koch and Vögele (2009). Once-through systems result in higher temperatures of the water body into which used water is being discharged because the water for cooling is discharged directly to the same water body after leaving the condenser. Excess temperature of the water body can be avoided by installing a cooling tower. The cooling tower uses an air stream in order to cool down the water before discharge, while a large share of the waste heat produced during the thermal cycle of the power plant is discharged through evaporation, thus leaving a lower quantity of water back to the water body. Closed circuit systems recirculate the cooled water back to the condenser, thus decreasing water withdrawal and affecting the temperature of the water body in a minimum way. As Koch and Vögele (2009) state, however, closed circuit systems relate to lower plant efficiencies.

Koch and Vögele (2009) conclude that power plants with closed circuit cooling systems are less vulnerable to fluctuations of temperature. In particular, they find that in a closed circuit system the increase in water demand is only 2% whereas plants with a once-through cooling system present an increase in water demand of 30%. In case water temperature is taken into consideration, power plants with closed circuit systems show a similar increase (Figure 1).

As mentioned in the case of nuclear power technology, planning of a low-carbon power system should incorporate factors of vulnerability to irreversible future climate change. Carbon capture and storage (CCS) technology features similar problems because it can double the demand for water of a thermal power plant, mainly for two reasons. First, the operation of a CCS system requires large amounts of electricity thus increasing the water demand of the actual installation if this additional power is supplied by conventional thermal sources. Second, an additional cooling load is created caused by the heat generated by the amine CO_2 absorption and the compressing of CO_2. According to NETL (2009) and Moore (2010), by 2030 CCS technology can increase water consumption of the US power sector by 80%. Chandel et al. (2011) give lower estimations of the increase in water consumption caused by the integration of CCS technology. In their paper, they analyze the impacts of climate policy-driven future power systems on freshwater use. In their analysis, the power mix alters according to the value of the carbon price, and all new thermal power plants are assumed to use recirculating cooling systems. They find that in a carbon-constrained power system with increased renewable and nuclear penetration, freshwater withdrawals are 2–14% lower than in business-as-usual (BAU) scenario. Actual consumption of freshwater is found near BAU levels in all cases except when the carbon price exceeds US\$50 ton^{-1} CO_2 and retrofitting of CCS is found cost-efficient. In Chandel et al. (2011), however, CCS technology contributes to a 15% increase in water consumption of the US power system. On the contrary, photovoltaic and wind technology contribute to a 20% reduction of water demand if renewables are substituted for coal plants.

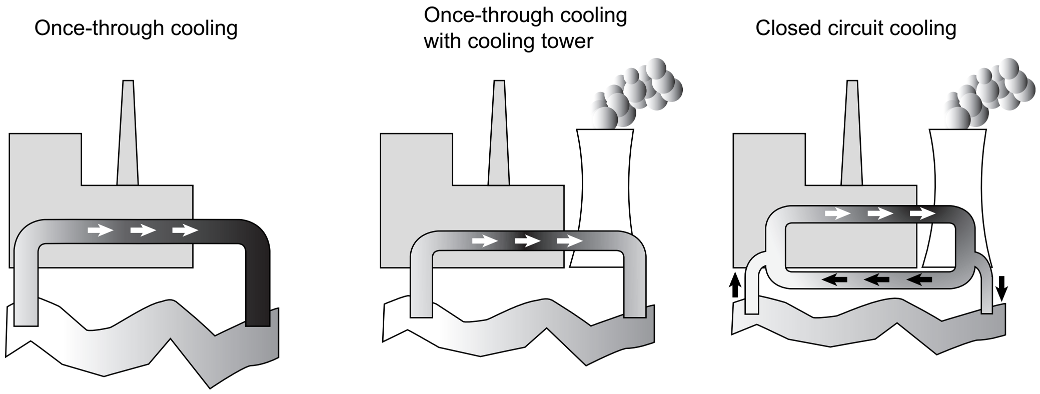


Figure 1

On a European level, Rubbelke and Vogele (2010) examine different scenarios to assess the impact of climatic changes to electricity exchange. They find that in a scenario with increased water scarcity, France will be obliged to reduce its electricity exports because of the large share of nuclear in the country's power mix, which makes it vulnerable to climate variability. Spain and Switzerland will also have to limit nuclear production and subsequent exports. The power system in Germany, although prone to cooling problems, is found easier to adapt. Other countries, like Italy, are affected by reduced cheap imports from France, and so on and thus have to increase domestic supply or find alternative exporters.

Adaptation measures include the consideration of efficient cooling systems and even the installation of water reuse systems, with appropriate treatment in order to protect equipment from increased saline levels. Moreover, once old power plants are to be decommissioned, they are expected to be replaced by more efficient ones that will require lesser amounts of water (and primary energy resources) for the production of 1 kW. Recirculating cooling systems or dry and hybrid air cooling are favorable in terms of water consumption. The latter, however, should not be installed in power plants located in regions expected to face high temperatures, as Chandel et al. (2011) note. An increase in ambient temperatures can also increase water temperatures and affect the plant's cooling efficiency even in wet cooling systems by increasing the demand for water.

Integrated gasification combined-cycle and oxyfuel plants are considered more efficient technologies in terms of water withdrawal and consumption, especially if CCS technology is to be used in order to minimize greenhouse gas emissions. The impact of CCS retrofit on water demand is reduced if amine systems are replaced with postcombustion capture technologies. Overall, research efforts are being made to develop technologies that are less water intensive. Feeley et al. (2008) emphasize the importance of R&D programs that aim at developing technologies that will enable improved water resource management practices in the power sector.

Planning of maintenance shutdowns should take into consideration temperature and water supply parameters; maintenance could be scheduled during months of increased temperatures like July or August in order to avoid unexpected capacity cuts (Rubbelke and Vogele 2010). Moreover, the optimum location of new plants must consider expected long-term impacts of climate variability to the neighboring water body, such as river runoffs, and avoid water-stressed areas.

Power companies that face difficulties related to water supply or legislation on permissible temperature of water discharges have respected their contractual agreements with their customers by purchasing electricity from other utilities. This highlights the importance of power mix diversification, especially in areas that are expected to be affected severely by climate variability. Different forms of power production are affected in a different manner by climate change and thus security of supply can be achieved only by a combination of production technologies. A region highly dependent on nuclear production or thermal power plants with CCS must consider a diversification of future power plant investments in order to avoid extended outages.

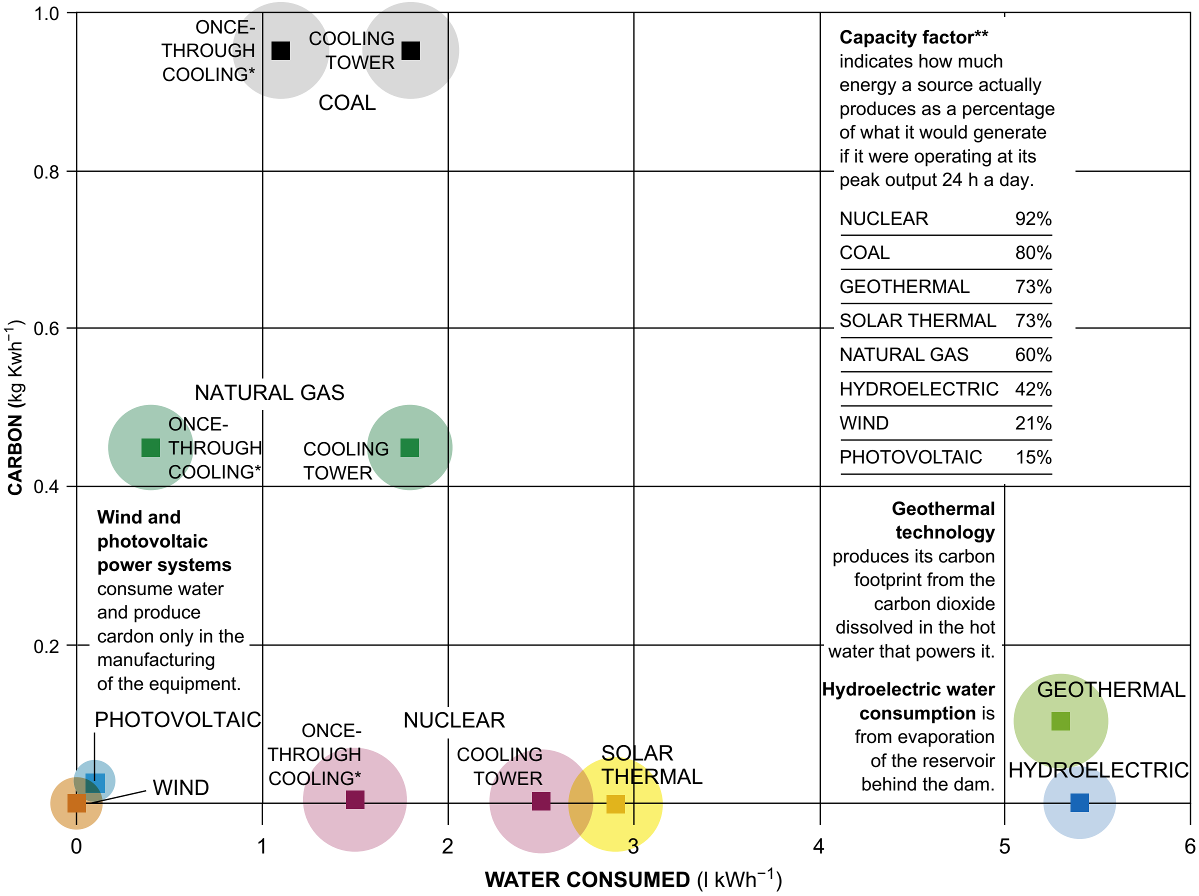
For more information on the water dependence of power plants, see the special IEEE report http://spectrum.ieee.org/static/special-report-water-vs-energy. **Figure 2** comes from the analysis undertaken by IEEE in its report and shows the water and carbon intensity of power technologies.

Impacts of Sea Level Rise and Intense Foods on Plant Operation and Security

Nuclear reactors and other thermal plants are often located along the coasts because of their requirements for water aimed for cooling. A world map of the sites of nuclear plants, which has been created from the extensive database of the International Atomic Energy Agency (http://gcmd.nasa.gov/records/GCMD_GNV181.html), shows that a considerable number of nuclear plants are located along coastlines. Nuclear power plants are given special consideration, owing to the dangerous consequences of possible damage to their equipment and installations. However, regular thermal power plants are also often located on coasts and may face similar difficulties to the ones described below.

A look at past events can distinctly reveal the vulnerability of nuclear plants relating to their location. The catastrophic accident in Fukushima nuclear plant in Japan occurred mainly because of the tsunami wave that ensued after the earthquake, whereas floods (e.g., Missouri River in 2011), storms, and hurricanes (e.g., Katrina in 2005) have posed significant risks to nuclear plant operation on several occasions. Problems related to the events mentioned may include fatal malfunctions of the reactors, the fire-safety systems, or the security and/or communication systems, thus putting in danger the safe operation of the power plants. During past events it has been seen that it is crucial to maintain access to external provision of electric power in order to be able to cool the reactor's cores. Moreover, extreme weather events may cause more floods and thus put in danger the plant's operation by flooding installations, damaging equipment, and stopping communication between the plant and external operational systems. This was the case in the 1999 flooding event in Le Blayais nuclear plant in France and more moderately in 2003 again in France, where according to Kopytko and Perkins (2011), mud and debris in the water used for cooling purposes caused damage to the cooling system and led to the shutting down of nuclear plants in the affected area.

Climatic change is expected to result in a rise of sea level, thus causing concerns for all infrastructure located on the coastlines. Although power plants are usually located a few meters or tens of meters above the sea and the mean sea level rise is not expected to reach that magnitude, sea level rise may in some cases interfere with the functionality of coastal installations (e.g., Committee on National Security Implications of Climate Change for US Naval Forces) through waves and risen sea level that is created from storms and hurricanes. The latter are actually expected to have a more severe impact on coastal installations through flooding and wind damage whereas mean sea level rise is expected to create coast erosion and inundation at reactor sites. Other impacts to nuclear production caused by climatic variability may include increased salt sprays that have a long-term effect of corrosion on the plant's equipment. Measures to reduce the vulnerability of thermal plants to sea level rise and extreme weather events



**Once-through cooling* dumps heat into surface water and returns the water to its source. Relatively little water is actually consumed by evaporation, but much more water must be available for the power plant to withdraw.

**Circle size indicates capacity factor.

Figure 2

include careful siting for new investments and advanced weather monitoring systems for all new and existing plants that can enhance timeous reactions.

As Kopytko and Perkins (2011) conclude in their research findings on the vulnerability of US coastal nuclear plants, most plants are found to have a high coastal vulnerability index mainly because of tides, storms, and increased sea level and less owing to erosion and waves. However, they conclude that coastal plants may face less severe consequences from climatic variability than inland plants especially if power demand is taken into consideration, because inland plants may have to force shutdown in periods of peak demand. On the other hand, costs related to adaptation measures or mere restructuring of damages is considerably high. Consequently, they pose the important questions on whether nuclear energy can be a safe and economically efficient mitigation tool, especially because climate variability is limiting the sites suitable for building nuclear plants.

Air Temperature Impacts on Plant Efficiency

In addition to increased water demand for cooling purposes, increasing ambient air temperature can affect the plant's thermal efficiency in a direct manner. The impacts from increased ambient temperature are closely related to each other because the heat differential between the engine and the external environment is reduced; hence, the plant's efficiency is reduced. In particular, ambient temperature affects the efficiency of the Brayton cycle, which in turn affects power output and fuel consumption by increasing the temperature of the air-specific volume of the compressor.

Davcock et al. (2004) have examined the impacts of ambient temperature on gas turbine performance. Their results indicate that a 33 °C increase in ambient temperature would decrease power output and heat rate of an open cycle gas turbine by 24 and 8.4%, respectively. Similar results are found by Kopac and Hilaci (2007) whereby under a 30 °C increase the overall efficiency of the plant is reduced by 4%. The analysis also indicates that ambient temperature has significant impacts on the exergy efficiency and irreversibility rate of the plant's boiler but lower effects on the outer components of the plant. Nevertheless, temperature increases caused by climate change are not expected to reach 30 °C as examined by the studies mentioned; hence, impacts on thermal efficiency are expected to be low.

Schaeffer et al. (2008) have examined the energy supply impacts of two main IPCC climate scenarios for Brazil. They find only 2% power output reduction for gas plants, thus conclude that impacts of increased temperature in Brazil's electricity supply are of an insignificant magnitude. Lineraud et al. (2009) find that a 1 °C temperature increase would affect thermal cooling and thus plant's power output by 0.8% for nuclear and 0.6% for gas plants. Though the results of the research work described previously shows low percentage levels of efficiency loss caused by an increase in ambient temperature, the impact in absolute terms of power output is significant and would require either new investments or would undermine the systems' security of supply.

3.14.2.2.2 Solar Power Plants

Renewable energy plants and in particular large power installations are susceptible to the impacts of climate change, similarly to thermal power plants discussed. Apart from resource vulnerability, which is directly related to climatic conditions owing to the intermittent nature of renewable sources, the installations can be vulnerable to external conditions.

Concentrated solar thermal power (CSP) plants are a promising type of renewable energy. CSP plants collect and concentrate direct sunlight through mirrors (either flat or parabolic) and then focus sunlight to an absorber tube. The central receivers at the top of the absorber tower contain a heat transfer fluid that is heated by direct sunlight and then used to produce superheated steam for the steam turbine generator and produce electricity. A key feature of this technology is the ability of thermal storage which enables operation even in the absence of direct sunlight. On the other hand, CSP technology requires direct sunlight and thus is more susceptible to solar irradiation conditions than PV plants. Because of the requirement of direct sunlight, arid areas are ideal for CSP installations, where solar irradiation is high, direct normal isolation is high, and weather is typically cloudless.

CSP production is based on thermal power generation and thus is characterized by similar aspects of climate vulnerability especially regarding ambient temperature increase. CSP installations are mainly located in arid areas and thus are well prepared for high temperatures. However, climate variability is expected to have distinctive impacts in desert environments; therefore, CSP development must take these into consideration. In addition, because of the intermittency of the energy input and the remoteness of the installations, CSP plant vulnerability to climate change should be assessed before large-scale development of this technology. Huge CSP plants are mentioned widely in the recent energy policy agenda. For example the Desertec project in North Africa is expected to supply clean and cost-efficient electricity to North Africa and Europe by 2050. In order to ensure higher levels of energy security for CSP energy systems, climate change vulnerability must be taken into consideration during planning procedures and the appropriate adaptation measures should be taken (Figure 3).

Reduced Visibility Effects

Sand storms are frequently found in deserts, for example, the Sahara, and are expected to be more frequent in the future because of climate variability; consequently sharp decreases of visibility in areas where CSP plants are installed may affect the plant's generation. Because CSP generation is based on direct sunlight, sand storms may cause the plant's shutdown or reduced operation according to storage options. Problems in

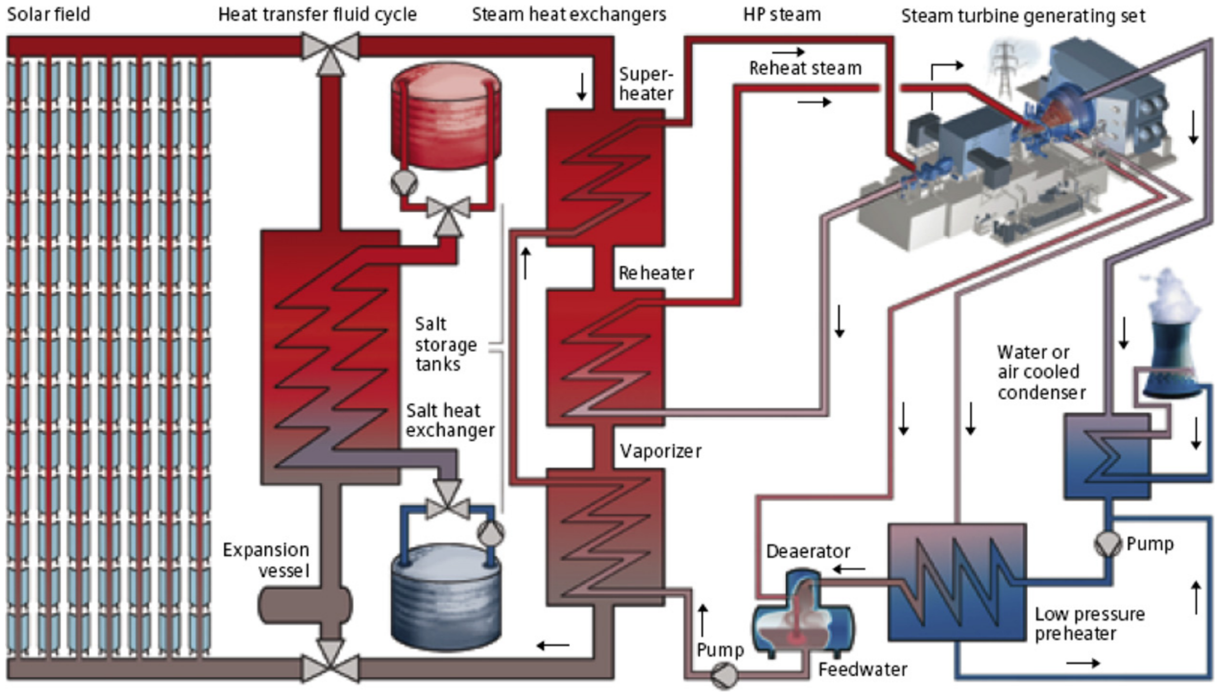


Figure 3

operation or damages of CSP plants during sand storms can be reduced with proper action of the on-site personnel. Examples of good practices include turning the mirrors upside down or covering them in order to avoid damages from sand blasting and proper cleaning of the mirrors after sand storms. On-site personnel are expected to be familiar with similar actions for optimal maintenance and operation of CSP plants on a daily basis, because mirrors will require cleaning in particular hours of the day owing to regular desert winds.

Another reason for reduced visibility and hence for reduced plant power output is increased and prolonged cloudiness. In particular, CSP plants rely on direct solar radiation and thus their operation ceases with diffused sunlight. For this reason, CSP plants are mainly developed in dry areas with short cloud coverage, but climate change may affect cloudiness owing to increased water precipitation, etc. Thermal storage capacity may reduce vulnerability to climatic conditions and substantially increase the plant's efficiency but with a subsequent increase of capital costs. Proper geographical dispersion would also reduce vulnerability of energy systems with high shares of CSP generation.

Temperature Increase Effects

CSP plants are based on thermal generation of a steam turbine which is, as described above, vulnerable to increases of ambient air and water temperature. With regard to water cooling demand, the impacts on CSP plants are expected to be minimal because most CSP plants rely on dry cooling owing to their arid siting. However, ambient temperature determines the efficiency of dry cooling, and according to Patt et al. (2010) a temperature increase from 30 to 50 °C will result in a 3–9% efficiency decrease. Because water cooling is not widely used in CSP plants, no plant outages are expected to be forced by plant operators owing to legislation that protects water temperature of rivers/lakes as in the case of nuclear and other thermal plants.

Research and development for new advanced technologies for parabolic or flat collectors, thermal storage, and dry cooling will determine CSP overall efficiency and vulnerability to climate change. Related considerations must be made prior to finalization of large investment plants that will determine the future energy systems of entire regions.

3.14.3 Conclusions

Energy systems have a key role in mitigating climate change but are also susceptible to climate changes. These two aspects should be central to determining energy policy and the energy systems of the future, along with cost-efficiency considerations and security of supply. Although the role of the energy sector in climate variability mitigation efforts is well understood and widely discussed, adaptation issues are not yet a high-priority policy agenda. It is important to build adaptive capacity that will ensure a secure energy system in spite of unavoidable climatic changes, thus research and development of new energy technologies must also focus on creating adaptive and resilient technologies. It is important to develop a basic knowledge capacity with regard to climate variability impacts on energy systems to avoid extremely vulnerable locations or types of technology.

Awareness, as regards the specific impacts to each energy source, may result in the development of different adaptation responses. Awareness rising from all the different stakeholders is important in order to achieve synergies and incorporate climate risk assessment in all levels of decision making and operation. Scientists, consumers, plant personnel, policy makers, and investors should all cooperate and acknowledge the criticality of adaptation. Scientists relate to new and improved technologies in power generation, more resilient to key climatic impacts. Consumers relate to demand responses and the development of small-scale distributed generation. Plant personnel are responsible for emergency planning and appropriate maintenance of the plant (i.e., cleaning, on-site drainage, and runoff). Finally, policy makers and investors relate to technology and location choice, both critical parameters for energy system vulnerability.

Technological responses relate to specialized research and development programs that will form the required knowledge capacity to achieve protection, better design, and new resilient, efficient, or even 'climate-proof' technologies. Some technological options in this direction are already available whereas others are in the development or demonstration stage. Technological measures include targeted retrofitting, for example, of dry cooling systems for thermal power plants instead of water cooling, or reinforcing of existing infrastructure and developing protective infrastructure such as increasing dam heights and enlarging floodgates.

Adaptation actions include strategic assessment of investments, for example in terms of location choice, as well as changes in operation and maintenance of plants in order to incorporate best practices (e.g., regular cleaning of CSP mirrors) or even include improved meteorological forecasting tools. Moreover, the impacts of climate variability may be reduced by introducing different generation technologies in the energy system, in particular technologies with different facets of climate vulnerability, and/or by introducing geographical dispersion. Diversification of the energy mix is important for hedging climate-related risks and creating resilient energy systems. Decentralized generation will also enhance climate resilience of energy systems, owing to geographical dispersion and reduced probability of large-scale outages.

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3.15 Transmission Grid Fundamentals

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3.15.1 Transmission Grid Overview

In this chapter, we present a brief overview of the transmission grid in the context of competitive energy markets. The transmission grid plays an essential role by providing the critical interconnection between suppliers and customers. It has been widely recognized that open access via the transmission grid is the key to a competitive electricity industry. However, the basic characteristics and limitations of the network must be properly addressed to achieve open transmission access. If transmission capacity for suppliers to reach customers is sufficient then the energy markets are simple and the market clearing straightforward. However, in most cases, transmission is a scarce resource and the transmission capacity limited. Hence, under normal conditions we need to deal with transmission congestion. The solution to the transmission congestion problem is fundamental to the way energy markets are designed and structured.

Congestion occurs when there is insufficient transmission capacity to simultaneously implement all energy transactions that market participants submit to a regional transmission organization (RTO) in the forward markets, or all actual energy flows that take place in real time. The major impact of transmission congestion is an overall increase in the cost of energy delivery. This cost is manifested by differences in the energy prices among injection and ejection locations in the network.

The simple example of **Figure 1** illustrates the impact of congestion in a system where a supply node A is connected to a demand node B through a transmission interface with maximum transfer capability q_{AB}. Absent congestion, the

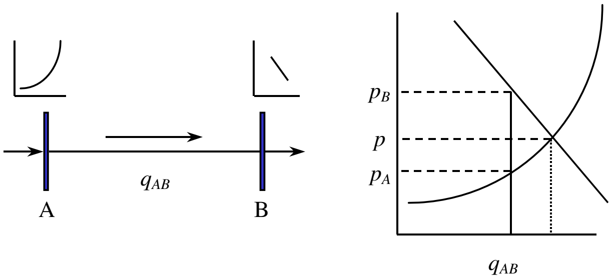

Figure 1 The impact of congestion.

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market would clear at the intersection of the supply and demand curves at price p. Because of congestion, only q_{AB} can be generated at A and consumed at B. This results in a lower price p_A at A and a higher price p_B at B. The price differential $p_B - p_A$ is the cost of congestion and corresponds to the congestion revenue that would be the outcome of a marginal cost settlement for energy: The demand at B would be charged p_B and the supplier at A would be paid p_A, resulting in congestion revenue. The congestion revenue is usually paid to the transmission owner, either directly or indirectly through transmission rights. In the latter case, the congestion revenue is paid to the transmission rights holders who acquire the rights from the transmission owner through an auction administered by the system operator, (RTO in the United States or transmission system operator (TSO) in Europe).

Financial transmission rights can be used as a hedge against congestion revenues (Treinen and Papalexopoulos 2002, 2005). In the example of **Figure 1**, if the supplier has a transmission right of q_{AB} on the interface A–B, in the direction from A to B, the supplier would be unaffected by congestion because the additional congestion revenue at the price difference of $p_B - p_A$ would elevate its effective price to that of the demand (p_B).

The simplest form of congestion management is deferring it to real time and clearing the forward energy markets as if there were no transmission constraints. This is equivalent to an unconstrained energy pool with a uniform forward energy price for the entire system. This is typical in many European market systems whereby the clearing by a power exchange produces a single price for an entire country. Congestion is addressed in real time by the TSO by an economic dispatch methodology that calculates optimal schedule adjustments to remove transmission constraint violations. To maintain a uniform price, these adjustments can be settled as bid and the net cost recovered by uplift. Clearly, the success of this approach would depend on the severity of congestion and the level of the uplift. If congestion is not small, forward energy market transactions could turn meaningless and large uplifts could distort price signals, creating perverse incentives in the marketplace. Even more significant is the so-called 'dec' game in which suppliers that cause congestion could end up being paid not to generate. This game was prevalent during the energy crisis in California in 2000 and 2001 (Joskow and Kahn 2001).

In a system where congestion cannot be ignored, some level of congestion management is necessary in the forward markets. The focus is to capture the effects of commercially significant and predictable congestion. This approach is compatible with the flow-gate model wherein congestion is observed only on flow-gates in the forward markets. Similarly, a zonal variation would observe congestion only on interzonal interfaces. Any remaining congestion would be insignificant or unpredictable (in which case hedging instruments are useless) and it would not be possible to effectively address it ahead of real time because of insufficient information. This congestion is effectively addressed in real time. It can be priced on the margin, using Locational Marginal Price (LMP) settlement, or settled as bid recovering the net cost by uplift. In this case, however, the uplift ought to be small because significant congestion is already mitigated in the forward markets.

If a detailed transmission network representation is required, congestion is observed in every path of the network. In this case even when one transmission constraint becomes binding, every location in the grid will clear at a different price, resulting in LMPs at every node in the transmission grid.

3.15.2 Transmission Grid Modeling

System operators deploy various methodologies and modeling techniques to study the steady-state operation of the transmission grid under postulated conditions. Various forms of optimal power flow (OPF) techniques and optimization technologies provide this capability. In particular, in the context of energy markets, the purpose of the OPF is to determine the impact of a generation and load pattern on the flows on the transmission grid. These flows can then be checked against operational limits to determine if there are any violations. Power flow (PF) analysis is also deployed to examine the impact of contingencies. This processing is referred to as security analysis.

The steady-state solution of the transmission network requires the solution of a set of nonlinear equations describing the balance of power at each location (bus). This is referred to as the dispatcher power flow (DPF) problem. The AC power flow equations, which describe the power balance at a bus, are a set of N complex equations, one for each bus, of the form

$$-P_{NET_k} + jQ_{NET_k} + V_k e^{-j\theta_k} \sum_{m=1}^{N} (G_{km} + jB_{km}) V_m e^{j\theta_m} = 0 \qquad k = 1, \ldots, N \qquad [1]$$

where

N = the number of electrical buses
V_m = the voltage magnitude at bus m
V_k = the voltage magnitude at bus k
θ_m = the voltage angle at bus m
θ_k = the voltage angle at bus k
$G_{km} + jB_{km}$ = the (k, m)th element of the bus admittance matrix
P_{NET_k}, Q_{NET_k} = the net real and reactive power injections at bus k.

The preceding set of complex equations can be separated into their real and imaginary parts forming two sets of (noncomplex) equations, which can be solved for an unknown set of V and θ.

$$\begin{aligned} &\sum_m P_{km}(V,\theta) - P_{NET_k} = 0 \quad k = 1, \ldots, N \\ &\sum_m Q_{km}(V,\theta) - Q_{NET_k} = 0 \end{aligned} \qquad [2]$$

where

$P_{km}(V,\theta)$ = the million watt (MW) flow on a branch connected between bus k and bus m
$Q_{km}(V,\theta)$ = the MVAR (unit that measures reactive power (1 MVAR = 1,000,000 VAR)) flow on a branch connected between bus k and bus m and the summation is performed over all branches connected to bus k.

The MW flow on the branch k–m can be written as

$$\begin{aligned} P_{km}(V,\theta) = {} & G_{kk}V_k^2 + V_k V_m (G_{km}\cos(\theta_k - \theta_m) \\ & + B_{km}\sin(\theta_k - \theta_m)) \end{aligned}$$

and the MVAR flow on the same branch can be written as

$$\begin{aligned} Q_{km}(V,\theta) &= -B_{kk}V_k^2 + V_kV_m(G_{km}\sin(\theta_k - \theta_m) \\ &\quad - B_{km}\cos(\theta_k - \theta_m)) \end{aligned}$$

The set of equations given by eqn [2] form what is commonly referred to as the Static Load Flow Equations (SLFE). These equations, along with several power flow local control features, form what is referred to as the dispatcher's power flow problem. The local control features are for maintaining a bus voltage at a specified value by varying a generator MVAR output, a transformer tap position, or a voltage control capacitor step position and for maintaining net interchange at a scheduled value. MVAR limits are respected on a generator during this process.

Sometimes, it is convenient to have a more compact notation for the above equations. This notation is shown in eqn [3].

$$G(X) = 0 \qquad [3]$$

where G is a set of nonlinear functions of a vector argument X. The vector argument X can be thought of as consisting of control variables, dependent variables, and fixed parameters. Some examples of the control variables are generator MW output, phase-shifter angles, and generator bus voltages. The dependent variables consist of bus voltage magnitudes and phase angles, as well as the MVAR output of generators performing bus voltage control. Fixed parameters are such items as the reference bus angle, noncontrolled generator MW and MVAR outputs, line parameters, etc.

There are two different algorithms that are commonly used to solve the DPF problem. One is the Newton–Raphson (NR) algorithm and the other is the Fast Decoupled Power Flow (FDPF). Both algorithms will be briefly described in the following sections. The NR algorithm will be described first because the FDPF algorithm is derived from the NR algorithm.

3.15.2.1 NR Algorithm

The basic purpose of the NR algorithm is to solve the SLFEs. These are represented by

$$G(X) = 0 \qquad [4]$$

The solution to these equations is based on the vector matrix Taylor series expansion of $G(X)$ about an initial state. The expansion is

$$G(X) = G(X^0) + J(X - X^0) + \text{higher order terms} \qquad [5]$$

where J is the Jacobian matrix:

$$J = \frac{\partial G(X)}{\partial X} \text{ evaluated at } X = X^0 \qquad [6]$$

The solution process should drive $G(X)$ to zero, so ignoring the higher order terms and letting $\Delta X = X = X^0$ yields

$$-J\Delta X = G(X^0) \qquad [7]$$

This equation is solved iteratively for a series of new states, X^k, until $|G(X^k)| \le \varepsilon$, a prespecified tolerance.

The basic algorithm is as follows:

1. Make an initial guess to the solution X^k with $k = 0$.
2. Evaluate $G(X^k)$. If maximum $|G(X^k)| \le \varepsilon$ then stop.
3. Build and factor J.
4. Solve eqn [7] for $\triangle X$.
5. Update X^k (i.e., $X^{k+1} = X^k + \Delta, k \leftarrow k+1$) and return to Step 2.

3.15.2.2 Fast Decoupled Power Flow Algorithm

The FDPF algorithm is another algorithm that may be used to solve the SLFEs (i.e., $G(X) = 0$). It is derived by making some simplifying approximations to the Jacobian matrix of the NR algorithm that lead to a more computationally efficient algorithm.

The first step in developing the FDPF algorithm is to reorder these equations so that all the real power balance equations are first, followed by the reactive power balance equations. This means that eqn [4] of that section may be rewritten as

$$\begin{bmatrix} \Delta P \\ \Delta Q \end{bmatrix} = \begin{bmatrix} HM \\ JL \end{bmatrix} \times \begin{bmatrix} \Delta\theta \\ \dfrac{\Delta V}{V} \end{bmatrix} \qquad [8]$$

where

ΔP, ΔQ represent the mismatch in the real and reactive power (respectively) that arises from ignoring the higher order terms (i.e., they correspond to $G(X_k)$)
$\Delta\theta, \Delta V/V$ correspond to ΔX
H, M, J, L submatrices which make up the Jacobian matrix.

These submatrices have the following definitions:

$$\begin{aligned} [H] &= \frac{\partial P}{\partial \theta} \\ [M] &= \frac{V\partial P}{\partial V} \approx [0] \\ [J] &= \frac{\partial Q}{\partial \theta} \approx [0] \\ [L] &= \frac{V\partial Q}{\partial V} \end{aligned} \qquad [9]$$

Elements of the off-diagonal submatrices, J and M, are much smaller in magnitude than elements of the diagonal submatrices, H and L, in the matrix equation, because of the weak coupling between the real power and the reactive power equations. Neglecting the off-diagonal coupling submatrices M and J, two sets of matrix equations are obtained:

$$\Delta P = [H] \times [\Delta\theta] \qquad [10]$$

$$\Delta Q = [L] \times \left[\frac{\Delta V}{V}\right] \qquad [11]$$

where $H_{km} = L_{km} = V_kV_m(G_{km}\sin\theta_{km} - B_{km}\cos\theta_{km})$

$$\begin{aligned} H_{kk} &= -B_{kk}V_k^2 - Q_k \\ L_{kk} &= -B_{kk}V_k^2 - Q_k \end{aligned}$$

Further simplifications are made by observing that in most realistic situations

$$\cos\theta_{km} \cong 1 \qquad [12]$$

$$G_{km}\sin\theta_{km} << B_{km} \qquad [13]$$

and

$$Q_k \langle\langle B_{kk} V_k^2 \tag{14}$$

With these approximations, eqns [10] and [11] reduce to

$$[\Delta P] = [VB'V] \times [\Delta\theta] \tag{15}$$

$$[\Delta Q] = [VB''V] \times \left[\frac{\Delta V}{V}\right] \tag{16}$$

where the elements of B' and B'' are based on the branch susceptance terms. Taking the left-most V terms to the left-hand side of the equations and setting the right-most V terms to 1 p.u. in eqn [15], as V affects the MVAR flows mainly, eqns [15] and [16] reduce to

$$\left[\frac{\Delta P}{V}\right] = [B'] \times [\Delta\theta] \tag{17}$$

$$\left[\frac{\Delta Q}{V}\right] = [B''] \times [\Delta V] \tag{18}$$

These equations are the FDPF equations. In calculating the elements of B' and B'', the following decoupling considerations are used: 1.1.1. Shunt elements and off-nominal transformers are neglected in B'; 1.1.2. Phase-shifter angle effects are neglected in B''; 1.1.3. Series resistances are neglected in B''.

The major advantage of these equations is that the matrices $[B']$ and $[B'']$ only need to be calculated and factored once. This gives the FDPF algorithm a speed advantage over the NR algorithm. The basic algorithm for solving these decoupled equations is as follows:

1. Enter with factors of B' and B''. Set ITP and ITQ $= 0$.
2. Compute $\Delta P/V$.
3. If P is not converged, go to Step 5.
4. If Q is converged, go to Step 9.
5. Solve $[B'] \times \Delta\theta = \Delta P/V$, update θ and ITP.
6. Compute $\Delta Q/V$.
7. If Q is converged, go to Step 9.
8. Solve $[B''] \times \Delta V = \Delta Q/V$, update V and ITQ.
9. If P and Q are converged, the solution is reached.
10. If ITP or ITQ exceed the maximum number of iterations, exit unconverged. Otherwise, go to Step 2.

There are a few items that should be noted. First, the simplifying approximations that have been made are only in the linearization of the problem about the initial point. The calculation of the mismatches is performed in detail with no approximations. The algorithm continues to iterate until the solution of $G(X) = 0$ is reached within a prespecified tolerance, usually 0.1 MW. Second, the modeling of control systems and other parameters, such as company interchange control voltage and transformer control, generator voltage-amperes reactive (VAR, unit that measures reactive power) limiting, distributed slack, matrix update, sensitivity calculations, contingency analysis, penalty factor calculation, power transfer distribution factor calculation, etc., are outside the scope of this chapter (Wood and Wollenberg 1984).

3.15.3 The Longer-Term Transmission Grid Problem

3.15.3.1 Problem Overview

There are few in the industry who would argue that the transmission system is currently well positioned to meet the growing demands of the restructured electric power industry. This applies not only to the physical infrastructure of the transmission networks, but also to the control and coordination of system operations.

Restructuring of the industry has fundamentally altered the nature of the electric power business to facilitate large regional competitive wholesale markets. New risk-reward–focused business models introduced to the upstream and downstream power markets provide market incentives beyond the former cost-of-service regulatory approach. At the same time, the continuing development of electric power spot markets has enabled a new breed of power marketers to trade power between low-cost and high-cost markets in response to both short- and long-term supply and demand fluctuations. Because electric power cannot be stored in a massive scale yet, but rather must be produced instantaneously as customers demand it, a robust transmission system is needed to allow these developing wholesale markets to function. These restructuring developments are increasing the reliance of industry – and the consumers that it serves – on the ability of the transmission system to operate dynamically in this new environment and its capability to handle short-term, market-driven power flow changes.

However, recent trends in transmission investment and system operation experience indicate that the transmission sector is not keeping pace with the changing dynamics in the wholesale (and retail) markets (Federal Energy Regulatory Commission 2006). The problem is further magnified with the high penetration of renewable energy in the grid mainly driven by policy mandates. The problems facing the transmission sector are based on two fundamental issues:

- The transmission system was not designed to support market-driven electricity trading and massive penetration of renewable resources into the power system.
- The transmission sector does not provide the incentives needed to support transmission investment and operations improvements necessitated by the changing industry structure and the policy mandates to support environmental goals. These policy mandates are prevalent in various forms in the United States and Europe today, as well as in other parts of the world.

As a result of increased wholesale market trading activity and massive penetration of renewable resources into the power system, we are witnessing the following major changes in the transmission system:

1. The pattern of transmission usage is changing; there is a greater reliance on the capabilities of the transmission grid interconnections between various energy markets.
2. The transmission system is under stress, and transmission expansion has not kept pace with the changes in the interstate electricity marketplace.
3. Transmission investments are lagging (Kaplan 2009).

As noted by the North American Electric Reliability Corporation (NERC), the use of advanced technologies such as superconducting materials, flexible AC transmission systems

(FACTS), or magnetic storage devices could improve transmission transfer capabilities over existing rights of way. However, the current framework does not provide significant incentives for rapid or large-scale transmission research and development initiatives.

The 'reasonable and prudent' stipulation embodied in regulation often requires a lengthy approval process and cost–benefit analyses, increasing the costs of development and delaying the benefits. In addition, to the extent that the introduction of new technology yields significantly increased benefits to system users as compared to conventional technology with similar costs, the transmission owner will not reap greater rewards but will face greater risks, if it pursues new technology under traditional cost-of-service regulation. This will make transmission owners broadly indifferent or even averse to the use of new technology, because they are not rewarded for exceptional performance and innovation.

Furthermore, even though transmission and generation investments are partial substitutes for each other in terms of meeting certain system requirements, generation is not always the most economically efficient means of solving a system problem. To the extent that the transmission system cannot deliver inexpensive electricity, more plants need to be built closer to load centers. Traditionally, in the vertically integrated utility structure, decisions affecting the trade-off between generation and transmission investment fell under a single locus of control, in which decisions were contingent primarily on state regulatory approval and oversight. Although state level regulatory control continues, business decisions concerning investment in these two types of resources under the new functionally unbundled industry structure are often in the hands of separate entities. As discussed, new merchant plants are often located at a distance from their target market, requiring transmission investments to be made even though the supply benefits will be realized elsewhere. The FERC noted this planning problem in Order No. 2000 (FERC Order 2000).

In certain situations, transmission solutions may be more appropriate than increased generation development. Some of the system externalities that may be more appropriately facilitated through transmission investment are the following:

- Expanded market competition through interconnection with multiple supply resources
- Reduced concentration in generation markets through interconnection with multiple supply resources
- Lower overall reserve requirements through access to capacity in neighboring regions
- Improved reactive power management
- Improved voltage stability
- Expanded flexibility in dealing with system emergencies and facilities outages

Although the economic decision between generation and transmission may be relatively clear, the lack of a balanced incentive structure between the generation and transmission sectors, coupled with the fragmentation of system planning among a larger group of market participants and the long schedules for building transmission compared to generation, has significantly tipped the investment balance toward generation.

FERC's Order No. 2000 attempted to rectify this situation. It provided for financial incentives to motivate transmission owners to join RTOs. Among these incentives is the open invitation by the FERC to consider various forms of incentive-based regulation for the transmission sector. This invitation to consider regulatory approaches other than traditional cost-of-service regulation is, in many ways, recognition of the increased risks and problems faced by the transmission sector and the inability of traditional regulation to effectively address these problems.

The emergence of the renewable industry over the last 10 years has further complicated the transmission problem. In many jurisdictions, transmission constraints, especially across market boundaries, or across countries in Europe, have become a major impediment to further penetration of renewable energy into the power system. Although some boundary crossing lines have been built in the past, that experience underscores a number of obstacles such projects face.

FERC's Order No. 1000 (Federal Energy Regulatory Commission 2011) attempts to encourage the development of a market environment that is conducive to the resolution of this problem. Unfortunately, there is too little useful transmission planning at regional, interregional, or interconnection-wide levels; the costs of boundary-crossing projects can be allocated only through project specific negotiations; and the need to obtain construction permits from multiple authorities makes it difficult to site and build boundary crossing lines. Some have argued that the best solution to this suite of problems is to construct a nationwide overlay or 'super-highway' grid (U.S. Department of Energy 2008). Others favor large, discrete transmission projects that connect sizeable renewable resources to major load centers. Still others defend a more conventional buildup of transmission reinforcements – within regions and across multiple regional boundaries – and more use of local renewable resources. Depending on the specific conditions of each project any of these options could provide the optimal outcome.

In the following subsection, we focus on specific major issues that are integral to the longer-term transmission problem.

3.15.3.2 Current Major Transmission Grid Challenges

In this section, we present the key challenges that continue to complicate investments in the transmission grid.

3.15.3.2.1 Transmission Planning

Traditionally, the transmission grid is expanded for reliability or economic reasons. The benefits of reliability are difficult to quantify and are often asserted to be spread over relatively wide areas. Only after reliability planning is complete do planners look for investments that would increase economic efficiency. Economic benefits include reduced network losses and mitigated or eliminated transmission constraints that prevent the use of the lowest-cost set of generators to meet demand. By strengthening the transmission grid, these projects also allow wholesale electricity markets to expand geographically, which mitigates market power and may provide other benefits. Of course, lines justified by economic benefits generally improve system reliability and vice versa (Joskow and Tirole 2005; MIT Study 2011). Recent years have seen very few transmission lines built that had been justified primarily on the basis of economic benefits. However, the emergence of the renewable energy is forcing policymakers and RTOs to create a new category for policy-driven transmission investments to accommodate this type of energy.

The planning process in most RTO regions is significantly more difficult than within vertically integrated utilities because decisions about the installation of new generation are the result of market forces (modified by state and federal support for renewables and other policies) rather than centralized planning. Thus, transmission planning in these regions is subject to additional uncertainties about where future generation may locate and how power will flow around the network, especially when renewable generators are involved. Magnifying this effect are uncertainties regarding future subsidies and requirements for renewable generation, because a painful fact of transmission planning is that it typically takes much longer to plan, get approvals, and build a high-voltage transmission line than a wind farm or solar generating facility. When generator build times are shorter than those for transmission, planners are forced to either anticipate new generation and build potentially unnecessary infrastructure or wait for firm generation plans before starting the process and thereby potentially discourage new generation investment.

Given the large distances required to transfer renewable energy to load centers, consideration of interregional projects one at a time rather than as parts of an interconnection-wide plan is no longer sensible. It has become obvious that making more use of remote renewables in an efficient manner will require permanent planning processes at the interconnection level.

According to FERC Order 2000, the key policy issues that need to be resolved with respect to transmission planning are as follows:

1. *What should be the objectives of the planning process*? For example, planning could be focused on renewable power development or on broader objectives, such as congestion relief and reliability enhancement.
2. *What should be the scope of authority of the planning entities*? Federal transmission planning could be run by interconnection-wide centralized authorities (the top-down approach) or be conducted primarily at a regional level (the bottom-up approach), or as a hybrid.
3. *What is the appropriate scope of the planning process*? Should the planning process extend beyond transmission planning narrowly defined to include a broader array of solutions to power system issues, such as demand response, distributed power, or conventional power plant construction.
4. *Could preferential treatment tied to the planning process distort transmission investment?* The planning proposals typically make available certain benefits, such as a federal permitting option, to projects included in the plan. These benefits could lead developers to add unnecessary features and costs to qualify proposals to meet plan criteria (e.g., proposing only high voltage lines if the plans have a minimum voltage threshold). Avoiding these distortions will require careful oversight or, arguably, limiting the benefits associated with the plan (e.g., putting all new power lines or none, whether or not they are in the plan, under federal government permitting authority).

3.15.3.2.2 Transmission Permitting

Interstate transmission projects require siting permits from every state the line will traverse. If any state disapproves a project, it will at best be delayed for rerouting or at worst canceled. As a result, projects are most vulnerable to challenge and litigation by parties who are not satisfied with the project for any reason. Challenges can take years to resolve. This permitting process has been a major obstacle to transmission investments.

At the federal level, the Energy Policy Act of 2005 gave FERC authority to issue permits for facilities in areas experiencing capacity constraints or congestion and designated by the Secretary of Energy as a National Interest Electric Transmission Corridor (NIETC). These permits would confer rights of eminent domain if a state commission or other entity with authority to approve siting has withheld approval for more than 1 year after the filing of an application seeking approval. However, subsequent Circuit Court decisions made this authority effectively irrelevant, ruling that FERC cannot act if a state simply rejects rather than withholds approval of a project it opposes and that the process to designate NIETCs was flawed. In summary, the parochial interests of the states and localities do not naturally encompass the broader interests of larger regions or of the nation as a whole. Similar policy issues apply to cross border transmission investments in Europe.

The simplest and most elegant solution to the problem of interstate transmission siting is to give FERC authority over significant interstate projects. Legislation should provide clear preemptive backstopping authority for FERC to site a transmission project after it has been approved by a regional planning entity, and a transmission project designated NIETC by Department of Energy (DOE). Legislation for electric transmission comparable to natural gas transmission should be desirable. It is, however, important to recognize that eliminating states' roles entirely has a variety of disadvantages, given their superior knowledge of local conditions (Willrich 2009). Similarly for Europe, we believe that a top-down approach is recommended where an EU authority plans for transmission upgrades across EU member States.

3.15.3.2.3 Transmission Financing and Cost Allocation

The funding of transmission investments unfortunately exhibits some characteristics of the 'chicken and egg' problem, particularly as it applies to renewable energy. Renewable energy plant developers may have difficulty getting funding because the transmission to bring their power output to market is not in place, whereas the transmission projects cannot get loans because the generation that would justify construction of the new lines has not been built. This early funding issue is exacerbated by the typical development pattern for many renewable energy projects. The projects are built in phases over several years. However, it is not economic to build a transmission line in phases; the line must be built at once for the maximum anticipated capacity even if the full load will not be developed until years after the line is first put into operation.

The most contentious transmission financing issue is cost allocation for new interstate transmission lines – that is, deciding which customers pay how much of the cost of building and operating a new transmission line that crosses several states. Clearly, cost allocation is the single largest impediment to any transmission development. Since cost allocation issues affect transmission siting, these two issues must be linked and managed simultaneously. This is an important point, and most current transmission proposals fold the cost allocation issue into the transmission planning process.

A simple way to resolve this problem is to allocate the costs of new projects that are part of an interconnection-wide plan to all customers in the interconnection (sometimes referred to as 'socializing' costs). The idea is that in a synchronized grid all ratepayers benefit to some extent from all transmission system enhancements. A related concept is that new transmission for renewable power yields environmental benefits to all ratepayers. A criticism of interconnection-wide cost allocation is that cost responsibility arguably becomes more diffuse and the incentives for cost discipline decline. Another criticism is that especially favorable funding for transmission could bias policymakers and investors away from other solutions to electric market problems, such as demand response or local renewable power. Other cost allocation approaches are being explored across the country but no approach is standard or even widely used (FERC Order 2000).

In summary, state and federal regulatory agencies should continue to authorize for proposed transmission projects rates of return on capital sufficiently high to attract financing from their traditional sources. Under normal conditions, the capital required to expand and modernize America's transmission grid may be attracted from the private sector. This assumes, however, a rational policy framework exists for planning, cost recovery and allocation, and siting of electric transmission facilities. Investor-owned utilities with strong balance sheets and independent transmission companies with requisite financial capacity should all play important roles in developing, financing, and owning the infrastructure.

3.15.4 Incentives for Transmission Investments

In this chapter, we present and analyze the risks transmission owners encounter in the restructured electric power industry and evaluate the potential for the emergency of merchant transmission grid expansions. In particular, we analyze the incentives financial transmission rights provide for the development of merchant transmission grid expansions.

3.15.4.1 Introduction

Just as restructuring of the electric power industry has increased and changed the risk profile of the predominantly deregulated wholesale and retail market participants, restructuring has also altered the risk profile of transmission owners. As regulated businesses, the increase in risk has not been as great for transmission owners as it has been for those upstream and downstream businesses more directly exposed to market forces. Nevertheless, risks do exist, including the following:

- **Financial strength** – Unbundled transmission entities are financially smaller than the former vertically integrated utility of which they were once a part.
- **Revenue diversity** – Transmission entities are largely dependent on a single revenue stream coming from their transmission assets, in contrast to a larger diversified stream of revenue derived from the combined generation, transmission, and distribution activities of the former vertically integrated utility. This reliance on a single revenue stream, though regulated, still places greater risks on the transmission owner.
- **Increased system demands** – Transmission owners and operators need to spend considerably more time optimizing the operation and maintenance of their transmission assets to facilitate the rapid growth in wholesale trading. This increasing reliance on the efficient operation of the transmission system under demanding conditions increases the system performance risks faced by the transmission owners and operators.
- **Increased market uncertainty** – The lack of a defined end-state configuration for the transmission sector in the restructured environment increases the uncertainty for transmission owners contemplating investments. Uncertainty over such issues as changing usage patterns arising from the continuing evolution of the wholesale and retail electricity markets and the high penetration of renewable energy could make seemingly sound investments today less valuable than anticipated in the future. Under-utilization of investments in the transmission grid poses a real threat to transmission investors and new methodologies are needed to ensure that this problem is mitigated.
- **Competitive threats** – Stand-alone transmission entities will face increased competitive threats, such as those from merchant transmission development and distributed generation. Given the mismatch between committing to long-lived (e.g., 40–50 years) investments to satisfy customer requests without similar length customer contracts, transmission owners are exposed to significant risks. It is tempting to say that this does not matter, because a regulated entity can just roll-in any such 'orphaned' costs and recover them through higher rates for the remaining customers. However, such actions will require increasing prices and could harm a company's competitive position.
- **Counterparty risk** – The growth of competition in the wholesale and retail electricity markets results in an expanding and changing variety of traders, marketers, aggregators, and other market participants requesting transmission service. This rapid increase in the number and diversity of transmission customers exposes transmission owners to increased counterparty financial risks that were not as prevalent for formerly vertically integrated utilities.
- **Increased regulatory uncertainty** – Significant uncertainty exists over the future regulatory rules for transmission. As we discussed earlier, it is imperative that a new framework of transmission investments is implemented where the key challenges of transmission planning, transmission permitting and siting, and financing and cost allocation are effectively addressed.

Whereas the risk profile for transmission owners and operators has increased, the reward structure has changed very little. Cost-of-service regulation still persists for almost every transmission owner in the United States. Although an increase in the allowed rate of return on transmission investment is not the sole solution to the industry's problems, it would signify the recognition of the increased risks faced by transmission owners. Increasing the allowed rate of return, either on new investment or the entire rate base, will improve the investment incentives for transmission owners, but it does not provide the necessary incentives for performance or customer service improvement. To address these issues, a new regulatory approach that provides incentives for both investment and performance improvement should be widely used.

However, as part of the regulatory framework there is room for merchant transmission additions within regional transmission systems, that is, transmission additions executed by private market participants. To the extent that the actual market-based cost/benefit of an interconnection is not appropriately reflected through the existing regulatory model, the construction of that asset as a merchant facility may be a way to overcome this regulatory gap and satisfy customer demand. Benefits to system users increase with greater coordination of transmission maintenance, investment, and other decisions affecting system availability and operation. This is one of the principal tenets behind the FERC movement to group transmission owners into large-scale RTOs: The larger the area under a single locus of control, the easier it will be to facilitate markets and deliver benefits to customers. Several researchers have argued that, under a stringent set of assumptions, the merchant investment model has a remarkable set of attributes that appear to solve the natural monopoly problem and the associated need for regulating transmission companies traditionally associated with electric transmission networks (Joskow and Tirole 2005). However, in practice, the merchant transmission model has not received substantial traction.

3.15.4.2 FTRs and Incentives for Expansion of the Transmission Grid

In principle, nobody should invest in grid expansions just to obtain rights to congestion rentals on the resulting additional capacity. Given the large economies of scale in grid investments, the principal effect of grid investments is to reduce or eliminate congestion rents. Additionally, the principal reason anybody would agree to pay part of the cost of a grid expansion is to create lower congestion charges for itself, which implies lower, not higher, congestion rents for the system. Thus, allocating Financial Transmission Rights (FTRs) to those who pay for a grid expansion will at best provide a minor increase in the incentive (or decrease in the disincentive) to join any coalition proposing to pay for a grid expansion.

Resolution of the inherent conflict between FTR holders and future investments could possibly be achieved by proper coordination between transmission expansion and the FTR auction timeline. A new transmission facility for example should not be made available before the currently effective FTRs expire so that there will not be an impact on the FTR value. The reduced value of FTRs due to the transmission expansion will then be reflected in the next FTR auction and there will be no damage to FTR holders.

Another related issue is the compensation to the investors that sponsor the transmission expansion. It is proposed that the investors will receive FTRs on the new transmission facilities. However, once new facilities are in place, the value of these FTRs may be substantially reduced. Therefore, the motivation for market forces in transmission expansion may become questionable. Furthermore, transmission expansion will usually benefit many more market participants than the investors, even participants that enter into the market after completion of the project. How can the costs and benefits of transmission expansion be allocated equitably? A regulatory backstop is required to manage a large project and allocate its costs to all users, if market forces fail to sort out all problems. If the project also benefits consumers, it is important to make distribution companies pay part of the costs, which, in turn, would add these costs to the distribution charges paid by customers.

3.15.4.3 Final Thoughts on Merchant Transmission Grid Expansions

The main issue related to merchant transmission grid expansions is the development of a regulatory system that fosters merchant transmission, who should pay for it, how much of it each will own, and how its cost will be recovered from future uses. Letting prospective alliances bid for a piece of the project based on their willingness to take risks on future usage is an idea worth trying – although adding FTRs to the process may not accomplish much, for the reasons outlined above. This process cannot provide a perfect solution to the problems of free riders and to the uncertainty about future usage. Nevertheless, there are no perfect solutions to these fundamental problems, and some version of this proposal may be feasible.

Unfortunately, where grid investments are concerned, there may be no good alternative to maintaining a significant role for central planning and regulation. The objective of minimizing central planning and regulatory intervention in the market is understandable and commendable. Unfortunately, markets work badly when externalities are large and property rights are poorly defined, as they inherently are on an electricity grid. New, sophisticated theories and systems, such as identification of the most significant congested paths and frequent updating of these paths because of system configuration changes, can be used to create property rights and internalize externalities, so that the role of the market can be safely expanded and the role of regulated central planning can be reduced. However, it can be dangerous to roll back planning and regulation too far before putting good market processes in place.

3.15.5 A Vision for Transmission

The uncertainties, risks, and challenges with respect to transmission grid investments presented in Section 3.24.4 have resulted in under-investment in the transmission infrastructure in many parts of the world. Clearly, the evolution of the transmission grid is not keeping up with the rapid changes in the generation sector. An additional major challenge transmission operators and planners need to deal with in the future is related to the vulnerabilities of the transmission grid owing to climate variability.

Climate vulnerabilities are mainly associated with the frequency and strength of weather extremes. The transmission grids are vulnerable to extreme events like flooding whereby cable networks or pipelines can be broken due to land erosion. Also, high amounts of snow can result in the overloading of electrical transmission lines, which therefore can be broken. Similar results are associated with falling trees caused by snow, high winds, or land erosion by the water streams. Strong winds at specific locations (e.g., gorges) can create vibration in the lines that may result in serious problems. Transmission lines near the coastlines are vulnerable to sea salt deposition that reduces the resistance with a potential of leaking and sparking. Furthermore, transmission lines are exposed to serious damage from overloading in case of heat waves. Any perturbation in weather conditions, and especially extreme weather conditions, can increase/decrease the vulnerability of the transmission grid. Substantial investment in the transmission infrastructure and sophisticated communication technologies, along with sound regulatory policies, are required to ensure the development of a robust transmission grid that can effectively address the challenges of rapidly changing energy sector.

Furthermore, the successful restructuring of the electric power industry in the United States and around the world depends, in large part, on the ability of the transmission sector to evolve and address the emerging problems facing the energy sector. These problems call for sound and bold implementation of innovative regulatory solutions and new business structures. The establishment of effective incentive regulation, coupled with unequivocal support for the development of for-profit transmission entities, offers the best solution to the mounting problems within the transmission sector. The additional revenues allowed to transmission entities for superior performance under such properly designed and implemented incentive plans would be more than repaid in cost savings and service benefits for electricity consumers. Consumers will benefit in several ways from a hybrid model of infrastructure development in which regulated and merchant transmission investments have an important role to play in securing a robust transmission sector. Even though the sector is not in crisis, major improvements in the regulatory and technological front are needed.

Resolution of the key challenges such as transmission planning, permitting and siting, and cost allocation will greatly contribute to sound transmission investments that can lead to:

1. Lower prices
2. Improved service and reliability
3. Balancing economically efficient investment decisions between transmission and generation
4. Adoption of new technologies

It is important to note that we should be concerned much more about under-investment in transmission than with overinvestment, because the societal costs of under-investment in transmission are much larger than the societal costs of overinvestment. External factors, such as licensing requirements, the need for rights of way, and 'not in my back yard' opposition to transmission infrastructure, already place significant constraints on overinvestment in major new transmission projects.

The transmission grid of the future will look very different than that of the past. The transmission grid of the past was built for a specific business and technical model: Power plants would use transmission lines to move electricity to distribution networks for delivery to customers. The power plants were large, central station facilities using fossil, nuclear, or hydroelectric energy sources, and were designed to run as-needed, when-needed. The power flow was one way, from the power plant to the customer. This model is already changing in major ways because of (1) variable renewable generation, (2) demand response, and (3) distributed generation. A key characteristic of these developments is potentially less predictability (in respect to availability and level of service) than traditional resources. The evolution of the current transmission model to an infrastructure with 'smart grid' capabilities is required to address these challenges.

The smart grid involves the integrated operation of the power system from the home to the power plant. It will provide improved real-time transmission monitoring and reliability and consumer energy management (FERC Order 2000). The transmission monitoring includes real-time monitoring of grid functions, improved automated diagnosis and responses to grid failure, 'plug and play' ability, and enhanced ability to manage high penetration of renewable energy into the grid. The consumer energy management, via the Advanced Metering Infrastructure (AMI), includes a two-way communication between the customer and the utility, ability to respond to high prices through links between the smart meter and the consumer's appliances, automated fault detection, easier management of distributed generation, and effective management of millions of connections of plug-in hybrid electric vehicles into the transmission grid. Finally, the smart grid is considered essential in managing the transition to a low-carbon economy and the successful implementation of sound environmental policies.

It is important also to mention that much opportunity for innovation remains on the demand side beyond smart meters and device-level price signaling. Microgrid distribution architectures of the future will require a finer level of coordination between power consuming devices and the transmission grid. This coordination will become possible as high speed networks such as Internet broadband and 4G cellular communications become universal and will involve devices with WiFi connectivity. This is what is known in high-tech circles as "the Internet of Things." These technologies will allow distributed generation resources across large populations of local wind and solar resources to be coordinated en masse, while ensuring local transmission and distribution constraints are met. The imprecise demand response programs of today will evolve to sophisticated network access control protocols analogous to those that govern communications devices that access wired networks and wireless spectrum such as Ethernet and Code Division Multiple Access (CDMA). Wide-scale distributed demand-side machine intelligence based on distributed computing-based stochastic control algorithms have recently been developed that provide fast and precise control over aggregate demand without significantly inconveniencing individual consumers (Ranade and Beal 2010). These innovations will result in a transmission grid architecture transformed from today's central generation and distribution 'fan' model to one where demand information flows upstream from end consumers to the grid operators and utilities. This transmission grid architecture will allow for a more self-organized, flattened, microgrid-based network model similar to the Internet to evolve.

In summary, the following recommendations are considered essential for the adoption of coherent and stable national policies on greenhouse gas emissions, electric vehicles, demand response, and renewable and distributed generation. These recommendations would enhance investment incentives and thereby accelerate the appropriate evolution of the grid.

1. Continue to support organized wholesale electricity markets along with open, nondiscriminatory access to the transmission grid.
2. Implement new legislation to grant FERC enhanced siting authority for major transmission facilities that cross state boundaries.
3. Implement a sound framework for addressing transmission planning, permitting, and cost allocation issues.
4. Encourage the implementation of the smart grid and various technologies that allow two-way communications between the grid operators/utilities and the customer devices.
5. Implement new emerging demand response management technologies that will allow for the emergence of flexible demand to be curtailed when necessary in the mass market.
6. Encourage R&D for the development and implementation of new algorithms, methodologies, software, and communication systems into the transmission grid operations.
7. Implement better methods and tools for the collection and dissemination of transmission data.

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Appendix A Fundamentals: Concepts of Electric Power Systems

An electric power industry is composed of three basic components: generation, which converts primary energy resources into electricity; distribution, which distributes electricity to millions of consumers at home, work, and play; and transmission, which connects generators to distributors. Among modern, industrially advanced nations, America's electric power industry is unique. It is largest in size, with about 1 000 000 MW of generating capacity, serving the largest economy in the world. To understand electric power systems, it is helpful to have a basic understanding of the fundamentals of electricity. These include the concepts of energy, voltage, current, direct current (DC), alternating current (AC), impedance, and power. The remainder of this section presents these basic concepts (Blume 2007).

A.1 Energy

Energy is the ability to perform work. Energy cannot be created or destroyed but can be converted from one form to another. For example, chemical energy in fossil fuels can be converted into electrical energy, and electrical energy in turn can be converted into useful work in the form of heat, light, and motion. Energy is measured in watt-hours (Wh) and for larger values is expressed in kilowatt (thousand watt, kW), megawatt (million watt, MW), gigawatt (billion watt, GW), or terawatt (trillion watt, TW) hours.

A.2 Voltage

Voltage (also referred to as potential) is measured between two points and is a measure of the capacity of a device connected to those points to perform work per unit of charge that flows between those points. Voltage can be considered analogous to the pressure in a water pipe. Voltage is measured in volts (V), and for large values expressed in kilovolts (kV) or megavolts (MV).

A.3 Current

Current is a measure of the rate of flow of charge through a conductor. It is measured in amperes (A). Current can be considered analogous to the rate of flow of water through a pipe. Current can be unidirectional, referred to as 'direct current,' or it can periodically reverse directions with time, in which case it is called 'alternating current.' Voltage also can be unipolar – in which one point is always at a higher voltage than the other – or alternating in polarity with time. Unipolar voltage is referred to as 'DC voltage' as in Figure 2.

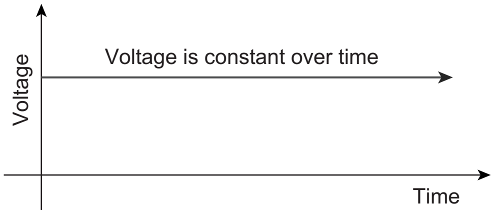

Figure 2 Direct current (DC voltage). Steven Blume, "Electric Power System Basics," IEEE Press Series on Power Engineering, Wiley 2007, a John Wiley & Sons, Inc. Publication.

Voltage that reverses polarity in a periodic fashion is referred to as "AC voltage" as in Figure 3.

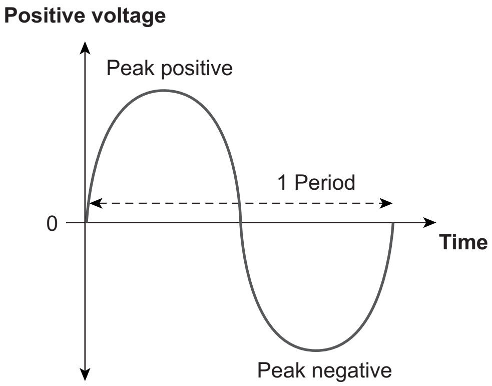

Figure 3 Alternating current (AC voltage). Steven Blume, "Electric Power System Basics," IEEE Press Series on Power Engineering, Wiley 2007, a John Wiley & Sons, Inc. Publication.

Alternating currents and voltages in power systems have nearly sinusoidal profiles. AC voltage and current waveforms are defined by three parameters: amplitude, frequency, and phase. The maximum value of the waveform is referred to as its 'amplitude.' Frequency is the rate at which current and voltage in the system oscillate, or reverse direction and return. Frequency is measured in cycles per second, also called 'hertz' (Hz). In the United States, as well as the rest of North America and parts of South America and Japan, the AC system frequency is 60 Hz, whereas in the rest of the world it is 50 Hz. DC can be considered a special case of AC, one with frequency equal to zero. The phase of an AC waveform is a measure of when the waveform crosses zero relative to some established time reference. Phase is expressed as a fraction of the AC cycle and measured in degrees (ranging from -180 to $+180°$). There is no concept of phase in a DC system.

A.4 Impedance

Impedance is a property of a conducting device – for example, a transmission line – that represents the impediment it poses to the flow of current through it. The rate at which energy flows through a transmission line is limited by the line's impedance. Impedance has two components: resistance and reactance. Impedance, resistance, and reactance are all measured in ohms.

A.5 Power

Power is the rate at which energy is flowing or work is being done. Because voltage is the amount of work done for each unit of charge that flows and current is the rate of flow of charge, the product of voltage and current is the rate of work – power, or more precisely instantaneous power. Because power loss is equal to the resistance of a conductor times the square of the current, loss in a transmission line can be reduced by increasing the transmission voltage, which allows the current to be reduced for the same amount of power transmitted. As a result, long transmission lines employ high voltage. However, high-voltage lines also have drawbacks, including the need to maintain larger clearances to maintain safety.

In AC systems, wherein voltage and current oscillate many times a second, the instantaneous power they produce is also rapidly varying. Negative instantaneous power is equivalent to power flowing in the backward direction. In electric power systems, it is more valuable to have measures of power that are averages over many cycles. These measures are real power, reactive power, and apparent power. Only two of these three measures are independent; apparent power can be determined from real power and reactive power.

Real power, also called 'active power' or 'average power,' is the average value of instantaneous power and is power that actually does work. It is measured in watts. Although instantaneous power can be flowing in both directions, real power only flows in one direction. Real power is zero if the phase difference between voltage and current is 90°.

If the voltage and current waveforms are 'in phase' – that is, they cross zero at the same time – then instantaneous power, although varying, is always positive or flowing in one direction. In this case, all the power is real power. However, if one waveform is shifted in time relative to the other, a condition called 'out of phase,' then power takes on both positive and negative values, as shown. This phase difference can arise, for example, because of the reactance of the transmission line. Here, in addition to the real power that is flowing in one direction, there is back and forth movement of power called 'reactive power.' While it does no useful work, reactive power flow still causes power losses in the system because current is flowing through components, such as transformers and transmission lines, which have resistance. Reactive power is measured in volt-amperes reactive (VAR).

Appendix B Electric Power System Structure

The electric power system consists of generating units where primary energy is converted into electric power, transmission and distribution networks that transport this power, and consumers' equipment (also called 'loads') where power is used. Although originally generation, transport, and consumption of electric power were local to relatively small geographic regions, today these regional systems are connected together by high-voltage transmission lines to form highly interconnected and complex systems that span wide areas. This interconnection allows economies of scale, better utilization of the most economical generators, increased reliability, and an improved ratio of average load to peak load due to load diversity, thus increasing capacity utilization. Interconnection also leads to complexity, however, as any disturbance in one part of the system can adversely impact the entire system (Blume 2007). We discuss each of its subsystems next.

B.1 Generation

Electric power is produced by generating units, housed in power plants, which convert primary energy into electric energy. Primary energy comes from a number of sources, such as fossil fuel and nuclear, hydro, wind, and solar power. The process used to convert this energy into electric energy depends on the design of the generating unit, which is partly dictated by the source of primary energy. The term 'thermal generation' commonly refers to generating units that burn fuel to convert chemical energy into thermal energy, which is then used to produce high-pressure steam. This steam then flows and drives the mechanical shaft of an AC electric generator that produces alternating voltage and current, or electric power, at its terminals. These generators have three terminals and produce three AC voltages, one at each terminal, which are 120° out of phase with respect to each other.

From the operational perspective of the electric power system, generating units are classified into three categories: base-load, intermediate, and peaking units. Base-load units are used to meet the constant, or base, power needs of the system. They run continuously throughout the year except when they have to be shut down for repair and maintenance. Nuclear and coal plants are generally used as base-load units, as are run-of-the-river hydroelectric plants. Intermediate units, also called cycling units, operate for extended periods of time but, unlike base-load units, not at one power continuously. They have the ability to vary their output more quickly than base-load units. Combined-cycle gas turbine plants and older thermal generating units generally are used as intermediate units. Peaking units operate only when the system power demand is close to its peak. They have to be able to start and stop quickly, but they run only for a small number of hours in a year.

Large generating units generally are located outside densely populated areas, and the power they produce has to be transported to load centers. They produce three-phase AC voltage at the level of a few to a few tens of kV. To reduce power losses during onward transmission, this voltage is immediately converted to a few hundred kV using a transformer. All the generators on a single AC system are synchronized. In addition to the main large generating units, the system typically also has some distributed generation, including combined heat and power units. These and other small generating units, such as small hydroelectric plants, generally operate at lower voltages and are connected at the distribution system level. Small generating units, such as solar photovoltaic arrays, may be single phase.

B.2 Transmission

The transmission system is the most complex machine man ever built. It carries electric power over long distances from the generating units to the distribution system. The transmission network is composed of power lines and stations/substations. Transmission system power lines, with rare exceptions, are attached to high towers. However, in cities, where real estate is valuable, transmission lines are sometimes made up of insulated cables buried underground. Stations and substations house transformers, switchgear, measurement instrumentation, and communication equipment. Transformers are used to change the level of the transmission voltage. Switchgear includes circuit breakers and other types of switches used to disconnect parts of the transmission network for system protection or maintenance. Measurement instrumentation collects voltage, current, and power data for monitoring, control, and metering purposes. Communication equipment transmits these data to control centers and also allows switchgear to be controlled remotely. Because transmission networks carry power over long distances, the voltage at which they transmit power is high to reduce transmission losses, limit conductor cross-sectional area, and require narrower rights-of-way for a given power. However, to maintain safety, high-transmission voltages require good insulation and large clearance from the ground, trees, and any structures.

Transmission voltages vary from region to region and country to country. The transmission voltages commonly (but not exclusively) used in the United States are 138, 230, 345, 500, and 765 kV. A voltage of 1000 kV has been used on a transmission line in China. Although most transmission is three phase AC, for very-long-distance transmission, High Voltage Direct Current (HVDC) can be beneficial because transmission lines present no reactive impedance to DC. HVDC also only requires two conductors instead of three. However, HVDC transmission lines require expensive converter stations (utilizing power electronics technology) at either end of the line to connect to the rest of the AC system.

Transformers at transmission substations convert transmission voltages down to lower levels to connect to the sub-transmission network or directly to the distribution network. Subtransmission carries power over shorter distances than transmission and is typically used to connect the transmission network to multiple nearby relatively small distribution networks. In the United States, the commonly used sub-transmission voltages are 69 and 115 kV.

The power that can be transmitted on a transmission line is limited by either thermal, voltage stability, or transient stability constraints, depending on which is the most binding. The thermal constraint arises because of the resistance of the transmission line that causes excessive power losses and hence heating of the line when the power flowing through it exceeds a certain level. The voltage stability constraint arises because of the reactance of a transmission line that causes the voltage at the far end of the line to drop below an allowable level (typically 95% of the nominal design voltage level) when the power flowing through the line exceeds a certain level. The transient stability constraint relates to the ability of the transmission line to deal with rapid changes in the power flowing through it without causing the generators to fall out of synchronism with each other. Generally, maximum power flow on short transmission lines is limited by thermal constraints, while power flow on longer transmission lines is limited by either voltage or transient stability constraints. These power flow constraints cause so-called congestion on transmission lines, when the excess capacity in the lowest-cost generating units cannot be supplied to loads due to the limited capacity of one or more transmission lines. Some very large consumers take electric power directly from the transmission or sub-transmission network. However, the majority of consumers get their power from the distribution network.

B.3 Distribution

Distribution networks carry power the last few miles from transmission or sub-transmission to consumers. Power is carried in distribution networks through wires either on poles or, in many urban areas, underground. Distribution networks are distinguished from transmission networks by their voltage level and topology. Lower voltages are used in distribution networks, as lower voltages require less clearance. Typically, lines up to 35 kV are considered part of the distribution network. The connection between distribution networks and transmission or subtransmission occurs at distribution substations. Distribution substations have transformers to step voltage down to the primary distribution level (typically in the 4–35 kV range in the United States). Like transmission substations, distribution substations also have circuit breakers and monitoring equipment. However, distribution substations are generally less automated than transmission substations.

Distribution networks usually have a radial topology, referred to as a "star network," with only one power flow path between the distribution substation and a particular load. Distribution networks sometimes have a ring (or loop) topology, with two power flow paths between the distribution substation and the load.

B.4 Load

Electricity is consumed by a wide variety of loads, including lights, heaters, electronic equipment, household appliances, and motors that drive fans, pumps, and compressors. These loads can be classified based on their impedance, which can be resistive, reactive, or a combination of the two. In theory, loads can be purely reactive, and their reactance can be either inductive or capacitive. However, in practice the impedance of most loads is either purely resistive or a combination of resistive and inductive reactance. Heaters and incandescent lamps have purely resistive impedance, whereas motors have impedance that is resistive and inductive. Purely resistive loads only consume real power. Loads with inductive impedance also draw reactive power. Loads with capacitive impedance supply reactive power. Because of the abundance of motors connected to the network, the power system is dominated by inductive loads. Hence, generating units have to supply both real and reactive power. Because capacitors produce reactive power, they often are connected close to large inductive loads to cancel their reactive power (i.e., increase the effective power factor of the load) and reduce the burden on the network and the generators. From the power system's operational perspective, the aggregate power demand of the loads in a region is more important than the power consumption of individual loads. This aggregate load is continuously varying.

Appendix C Fundamentals of Transmission Networks

C.1 Overview

High-voltage transmission lines transport power over long distances much more efficiently than lower-voltage distribution lines for two main reasons. First, high-voltage transmission lines take advantage of the power equation, that is, power is equal to the voltage times current. Therefore, increasing the voltage allows one to decrease the current for the same amount of power. Second, since transport losses are a function of the square of the current flowing in the conductors, increasing the voltage to lower the current drastically reduces transportation losses. Plus, reducing the current allows one to use smaller conductor sizes. Therefore, we increase the voltage to reduce the current and the losses (Blume 2007).

A typical high-voltage transmission line is a three-phase 500 kV transmission line with two conductors per phase. The two-conductors-per-phase option is called *bundling*. Power companies bundle multiple conductors – double, triple, or more – to increase the power transport capability of a power line. The type of insulation used in this line is referred to as *V-string* insulation. V-string insulation, compared with *I-string* insulation, provides stability in wind conditions. This line also has two *static wires* on the very top to shield itself from lightning. The static wires in this case do not have insulators; instead, they are directly connected to the metal towers so that lightning strikes are immediately grounded to earth. Hopefully, this shielding will keep the main power conductors from experiencing a direct lightning strike.

Transmission lines can be built overhead or underground. Underground transmission is usually 3–10 times more costly than overhead transmission owing to right of way requirements, obstacles, and material costs. It is normally used in urban areas or near airports where overhead transmission is not an option.

Also DC transmission systems are sometimes used for economic reasons, system synchronization benefits, and power flow control. In this case, the three-phase AC transmission line is converted into a two-pole (plus and minus) DC transmission line using bidirectional rectification *converter stations* at both ends of the DC line. The converter stations convert the AC power into DC power and vice versa. The reconstructed AC power must be filtered for improved power quality performance before being connected to the AC system. DC transmission lines do not have phases; instead, they have positive and negative *poles*. There are no synchronization issues with DC lines. The frequency of DC transmission is zero and, therefore, there are no concerns about variations in frequency between interconnected systems. A 60-Hz system can be connected to a 50-Hz system using a DC line. For economic reasons, a DC line may have advantages over the AC line, because the DC lines have only two conductors versus three conductors in AC lines. The overall cost to build and operate a DC line, including converter stations, may cost less than an equivalent AC line owing to the savings from one less conductor, narrower right of ways, and less expensive towers.

The major types of equipment found in most transmission and distribution substations are presented next. Detail exhibition of the purpose, function, design characteristics, and key properties of each equipment is outside the scope of this chapter. The substation equipment includes (1) transformers, (2) regulators, (3) circuit breakers and reclosers, (4) air disconnect switches, (5) lightning arresters, (6) electrical buses, (7) capacitor banks, (8) reactors, (9) static var compensators, (10) control building, and (11) preventative maintenance equipment. We'll close this section with a brief summary of conductors and conductor types and sizes.

C.2 Conductors

Conductor material (all wires), type, size, and current rating are key factors in determining the power handling capability of transmission lines, distribution lines, transformers, service wires, and so on. A conductor heats up when current flows through it owing to its resistance. The resistance per mile is constant for a conductor. The larger the diameter of the conductor, the less resistance there is to current flow. The amount of current that causes the temperature to rise depends on the conductor material and size. The conductor type determines its strength and application in electric power systems.

Utility companies use different conductor materials for different applications. Copper, aluminum, and steel are the primary types of conductor materials used in electrical power systems. Other types of conductors, such as silver and gold, are actually better conductors of electricity; however, cost prohibits wide use of these materials.

C.3 Conductor Types and Size

Power line conductors are either solid or stranded. Rigid conductors such as hollow aluminum tubes are used as conductors in substations because of the added strength against sag in low-profile substations when the conductor is only supported at both ends. Rigid copper bus bars are commonly used in low-voltage switchgear because of their high current rating and relatively short lengths. The most common power line conductor types are (1) solid, (2) stranded, and (3) aluminum conductor, steel-reinforced (ACSR). With respect to the size, there are two conductor size standards used in electrical systems. One is for smaller conductor sizes (American Wire Gauge) and the other is for larger conductor sizes (circular mils).

Volume 4

Climate Vulnerability

Understanding and Addressing Threats to Essential Resources

Volume 4: Vulnerability of Ecosystems to Climate

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EDITOR-IN-CHIEF

Roger A. Pielke, Sr.

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VOLUME 4

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He has studied terrain-induced mesoscale systems, including the development of a three-dimensional mesoscale model of the sea breeze, for which he received the NOAA Distinguished Authorship Award for 1974. He has worked for NOAA's Experimental Meteorology Lab (1971—74), The University of Virginia (1974—81), and Colorado State University (1981—2006). He served as Colorado State Climatologist from 1999—2006. He was an adjunct faculty member in the Department of Civil and Environmental Engineering at Duke University in Durham, North Carolina (July 2003—06). He was a visiting professor in the Department of Atmospheric Sciences at the University of Arizona from October to December 2004.

He has served as chairman and member of the AMS Committee on Weather Forecasting and Analysis, and was the chief editor for the Monthly Weather Review for 5 years from 1981 to 1985. In 1977, he received the AMS Leroy Meisinger Award for 'fundamental contributions to mesoscale meteorology through numerical modeling of the sea breeze and interaction among the mountains, oceans, boundary layer, and the free atmosphere'. He received the 1984 Abell New Faculty Research and Graduate Program Award, and also received the 1987/1988 Abell Research Faculty Award. He was declared 'Researcher of the Year' by the Colorado State University Research Foundation in 1993. In 2000, he received the Engineering Dean's Council Award from Colorado State University.

He authored a book published by Academic Press entitled 'Mesoscale meteorological modeling' in 1984 with a 2nd edition in 2002, a book for Routledge Press entitled 'The Hurricane in 1990, a book (coauthored with W.R. Cotton) for Cambridge Press entitled 'Human impacts on weather and climate in 1995; 2nd ed., 2006, a book (coauthored with R.A. Pielke, Jr.) entitled 'Hurricanes: Their nature and impacts on society' published in 1997 by John Wiley and Sons, and was co-chief editor (with R.A. Pielke, Jr.) of a book entitled 'Storms' published by Routledge Press in 1999.

He was elected as a fellow of the AMS in 1982 and fellow of the American Geophysical Union in 2004. From 1993—96, he served as editor-in-chief of the US National Science Report to the IUGG (1991—94) for the American Geophysical Union. From January 1996 to December 2000, he served as co-chief editor of the *Journal of Atmospheric Science*. In 1998, he received NOAA's ERL Outstanding Scientific Paper (with Conrad Ziegler and Tsengdar Lee) for a modeling study of the convective dryline. He was designated a Pennsylvania State Centennial Fellow in 1996, and named the Pennsylvania State College of Earth and Mineral Sciences Alumni of the year for 1999 (with Bill Cotton). He is currently serving on the AGU Focus Group on Natural Hazards (August 2009—Present) and the AMS Committee on Planned and Inadvertent Weather Modification (October 2009—Present). He is among one of three faculties and one of four members listed by ISI Highly Cited in Geosciences at Colorado State University and the University of Colorado at Boulder, respectively.

He has published over 370 papers in peer-reviewed journals, 55 chapters in books, coedited 9 books, and made over 700 presentations during his career to date. The listing of papers can be viewed at the project website: http://cires.colorado.edu/science/groups/pielke/pubs/. He also launched a science weblog in 2005 to discuss weather and climate issues. This weblog was named one of the 50 most popular Scienceblogs by Nature Magazine on 5 July 2006 and is located at http://pielkeclimatesci.wordpress.com/.

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VOLUME EDITORS

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Dr Dev Niyogi is an associate professor with joint appointment in the Departments of Agronomy and Earth, Atmospheric, and Planetary Science at Perdue University.

He is also the State Climatologist for Indiana and Director of the Indiana State Climate Office. His research seeks to advance the understanding of vegetation and land surface processes in environmental, weather forecasting, and climate analyses, using a combination of dynamical models and surface, satellite remote sensing, and multiscale analysis products.

His research deals with the understanding and representation of the effects of vegetation – land surface processes in environmental processes at different scales. He is one of the three invited, nonfederal representatives to the community modeling effort of the Weather Research and Forecast (WRF) model working group on Land Surface Models, and to the Federal Geophysical Data Commission (FGDC) Spatial Climate Working Group.

He has authored or coauthored 25 successful proposals for external grants totaling over $3M. He vertically integrates undergraduate, graduate, and postdoctoral researchers in his research and is very interdisciplinary in developing collaborative projects.

Dr George Kallos is a professor at the University of Athens, School of Physics, Division of Environmental Physics and Meteorology. He leads the Atmospheric Modeling and Weather Forecasting Group (AM & WFG). He has a BSc from the University of Athens/School of Mathematics (1975). He obtained his MSc (1983) and PhD (1985) in Geophysical Sciences/ Atmospheric Sciences Division, Georgia Institute of Technology, School of Geophysical Sciences, USA. He has 110 publications in peer review scientific journals, more than 230 presentations and publications in conference proceedings publications, 10 contributions in books and more than 200 other publications in subjects related to atmospheric physics and chemistry, sea-state conditions, and renewable energy production. He has been invited 70 times to give talks in conferences, seminars, etc. His published work has received >2000 citations. He has participated in 80 projects. He has organized 12 conferences related to air pollution and dust transport in the Mediterranean. He has supervised 10 PhDs and over 100 MSc theses and participated in 20 PhD examinations in Greece and Europe. He is an associate editor for the journals: '*Environmental Fluid Mechanics*', '*Advances in Meteorology*', '*International Journal of Geosciences*', '*Atmospheric Pollution Research*', and '*Journal of Aerospace Operations*'. He was awarded the International Union of Air Pollution Prevention Association – IUAPPA award for his work on 'Long-range transport and air quality work in the Mediterranean region'. His current research activities are related to atmospheric, climatic, air pollution, and sea-state model development and forecasting. He focuses in fully coupled modeling systems. The latest model developments are related to nucleation processes in clouds, desert dust cycle and its direct and indirect effects. Research activities related to renewable energy resources (wind, ocean, solar) are focusing on high accuracy atmospheric model development, energy relationships and predictions, and protection from extremes.

Timothy Seastedt received his BA in biology from the University of Montana, an MS degree in biological sciences from the University of Alaska at Fairbanks, and a PhD degree from the University of Georgia. He was on the faculty at Kansas State University and is currently a professor of Ecology and Evolutionary Biology and fellow of INSTAAR at the University of Colorado, Boulder. Much of his research has been conducted as part of the Long-Term Ecological Research (LTER) programs at KSU and CU. His interests focus on terrestrial ecosystem ecology and the causes and consequences of biotic change. His recent activities have emphasized the ongoing changes found along the grassland to (melting) glacier gradient that exists in the Colorado Front Range.

Katharine Suding received her BA in biology from Williams College and a PhD degree from the University of Michigan. She was on the faculty at University of California Irvine and is currently a professor in Environmental Science, Policy and Management at the University of California Berkeley. Her background is in plant community and ecosystem ecology, with current interests in restoration, resilience, and environmental change.

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PREFACE

We are pleased to introduce the five-volume set of books on bottom-up, resource-based vulnerability assessments of the societally and environmentally key resources of water, food, energy, human health and well-being, and ecosystem function. This inclusive bottom-up vulnerability concept requires the determination of the major threats to these resources from climate, but also from other social and environmental issues. After these threats are identified for each resource, the relative risk from natural- and human-caused climate change (estimated from global climate model (GCM) projections, as well as the historical, paleorecord, and worst case sequences of events) can be compared with other environmental and social risks in order to adopt the optimal mitigation and adaptation strategies.

The bottom-up, resource-based approach (referred to by O'Brien (2009) as ‘contextual vulnerability’) that is the focus of the volume is distinct from the Intergovernmental Panel on Climate Change (IPCC) top-down assessment of vulnerability based on the multidecadal GCM predictions (projections) which O'Brien defined as ‘outcome vulnerability’ (**Table 1** and **Figure 1**).

An excellent example of the contextual vulnerability is the paper by Romero-Lankao et al. (2012) who concluded in a study of the literature that urban vulnerability is dominated by epidemiological studies and top-down assessments, but that inherent urban vulnerability and urban resilience approaches (the contextual vulnerability) are what is required in order to illuminate a more complete set of drivers of urban vulnerability. They also showed that the large majority of papers on vulnerability use the outcome vulnerability approach. However, as discussed below, this top-down approach has major flaws.

First, there is the issue that the term ‘climate’ has two definitions. The broader view (and the one adopted by NRC (2005)) is that climate consists of the atmosphere, oceans, land, and cryosphere. This is the preferred usage. The second definition is that climate is the term used for the long-term (e.g., multidecadal) statistics of weather.

As reported in the NRC (2005) report and written in the Pielke et al. (2009) article with respect to human climate forcings.

> In addition to greenhouse gas emissions, other first-order human climate forcings are important to understanding the future behavior of Earth's climate. These forcings are spatially heterogeneous and include the effect of aerosols on clouds and associated precipitation [e.g., Rosenfeld et al. 2008], the influence of aerosol deposition (e.g., black carbon (soot) [Flanner et al. 2007] and reactive nitrogen [Galloway et al. 2004]), and the role of changes in land use/land cover [e.g., Takata et al. 2009]. Among their effects is their role in altering atmospheric and ocean circulation features away from what they would be in the natural climate system [NRC 2005]. As with CO_2, the lengths of time that they affect the climate are estimated to be on multidecadal timescales and longer.

and

> “…the natural causes of climate variations and changes are important, as are the human influences. The human climate forcings involve a diverse range of first-order climate forcings, including, but not limited to, the human input of carbon dioxide (CO2). Most, if not all, of these human influences on regional and global climate will continue to be of concern during the coming decades.”

Threats from climate involve any one or combination of climate variables as illustrated in **Figure 2**. There do not, of course, have to be changes in the statistics of these variables to constitute a risk. The term

Table 1 Contrast between a top-down versus bottom-up assessment of the vulnerability of resources to climate variability and change

Approach	*Comparative vulnerability*	*Contextual vulnerability*
Assumed dominant stress	Climate, recent greenhouse gas emissions to the atmosphere, ocean temperatures, aerosols, etc.	Multiple stresses: climate (historical climate variability, land use and water use, altered disturbance regimes, invasive species, contaminants/pollutants, habitat loss, etc.)
Usual timeframe of concern	Long-term, doubled CO_2 30–100 years in the future.	Short-term (0–30 years) and long-term research.
Usual scale of concern	Global, sometimes regional. Local scale needs downscaling techniques. However, there is little evidence to suggest that present models provide realistic, accurate, or precise climate scenarios at local or regional scales.	Local, regional, national, and global scales.
Major parameters of concern	Spatially averaged changes in mean temperatures and precipitation in fairly large grid cells with some regional scenarios for drought.	Potential extreme values in multiple parameters (temperature, precipitations, frost-free days) and additional focus on extreme events (floods, fires, droughts, etc.) measures of uncertainty.
Major limitations for developing coping strategies	Focus on single stress limits preparedness for other stresses. Results often show gradual ramping of climate change-limiting preparedness for extreme events. Results represent only a limited subset of all likely future outcomes – usually unidirectional trends. Results are accepted by many scientists, the media, and the public as actual 'predictions'. Lost in the translation of results is that all models of the distant future have unstated (presently unknowable) levels of certainty or probability.	Approach requires detailed data on multiple stresses and their interactions at local, regional, national, and global scales, and many areas lack adequate information. Emphasis on short-term issues may limit preparedness for abrupt "threshold" changes in climate sometime in the short or long term. Requires preparedness for a far greater variation of possible futures, including abrupt changes in any direction – this is probably more realistic, yet difficult.

Adapted from Kabat et al. 2004.

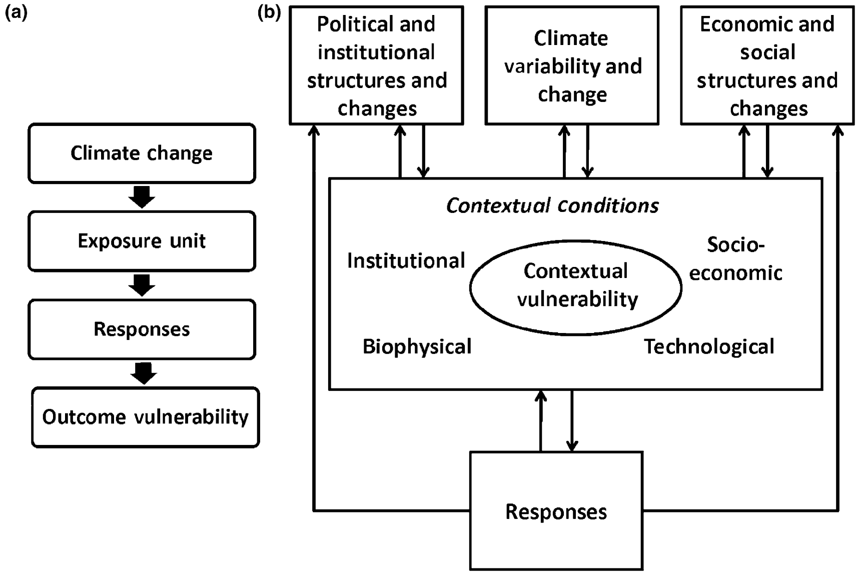
(a)
Climate change
Exposure unit
Responses
Outcome vulnerability
(b)
Political and institutional structures and changes
Climate variability and change
Economic and social structures and changes
Contextual conditions
Institutional
Contextual vulnerability
Socio-economic
Biophysical
Technological
Responses

Figure 1 Framework depicting two interpretations of vulnerability to climate change: (a) outcome vulnerability and (b) contextual vulnerability. *From: Füssel (2009) and O'Brien et al. (2007).*

'climate change' should be used to describe any multidecadal or longer alteration in one or more physical, chemical, and/or biological components of the climate system, but as explained below, this terminology has morphed into multiple, diverse (and often mutually exclusive) definitions as used by the impacts communities.

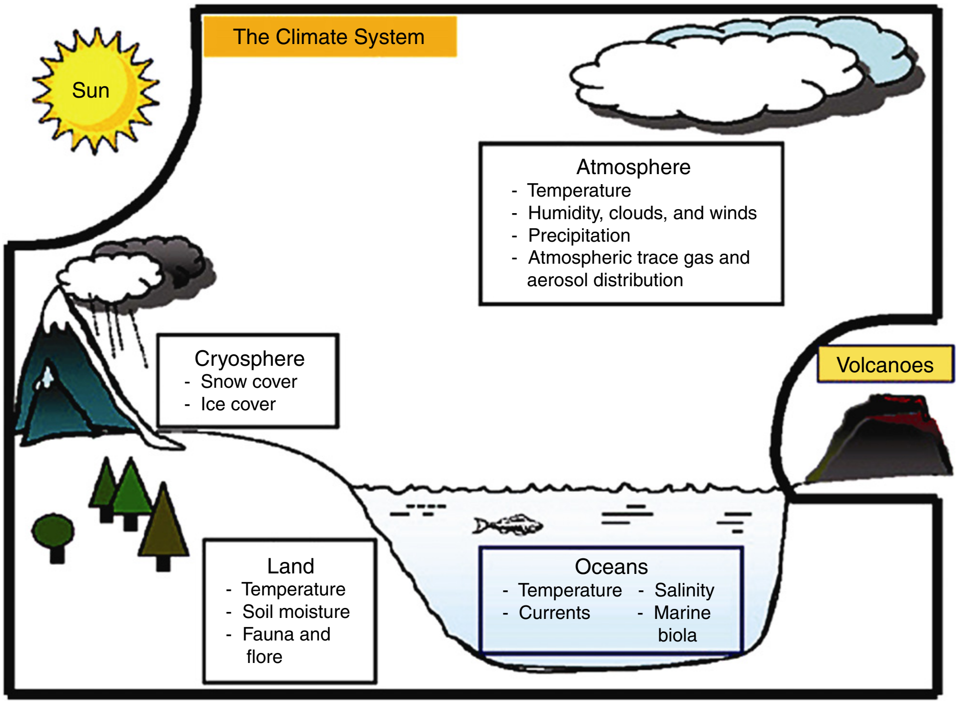
The Climate System
Sun
Atmosphere
- Temperature
- Humidity, clouds, and winds
- Precipitation
- Atmospheric trace gas and aerosol distribution
Cryosphere
- Snow cover
- Ice cover
Volcanoes
Land
- Temperature
- Soil moisture
- Fauna and flore
Oceans
- Temperature
- Currents
- Salinity
- Marine biola

Figure 2 The climate system, consisting of the atmosphere, oceans, land, and cryosphere. Important state variables for each sphere of the climate system are listed in the boxes. For the purposes of this report, the Sun, volcanic emissions, and human-caused emissions of greenhouse gases and changes to the land surface are considered external to the climate system (NRC 2005).

First, climate is never static (Lovejoy and Schertzer 2012). As written in Rial et al. (2004)

> "The Earth's climate system is highly nonlinear: inputs and outputs are not proportional, change is often episodic and abrupt, rather than slow and gradual, and multiple equilibria are the norm."

The assumption of a stable climate system (e.g., the reason for the use of the terminology 'climate stabilization') in the absence of human intervention is a mischaracterization of the behavior of the real climate system. Humans are now adding to the complexity of forcings and feedbacks, but change has always been a part of the climate system. 'Climate change' is, and always has, been occurring. The added word 'change' is, therefore, redundant.

Moreover, there are additional misunderstandings. 'Global warming', which is an increase in the global annual average heat content measured in Joules, is often incorrectly equated to mean 'climate change'. Global warming, however, is just a subset of "climate change."

The term 'climate change', is also being erroneously used to mean only 'anthropogenic caused changes in climate' from nearly 'static' climatic conditions. Frequently, just the human input of greenhouse gases is assumed to be the reason for 'climate change'. For example, NRC (2010) (Climate Stabilization Targets: Emissions, Concentrations, and Impacts Over Decades to Millennia (2010)) states

> "This new report from the National Research Council concludes that emissions of carbon dioxide from the burning of fossil fuels have ushered in a new epoch where human activities will largely determine the evolution of Earth's climate."

Thus, the recommendations to the authors of the volume (not always accepted) were to replace terminology, such as climate change, climate stabilization, and climate disruption, with accurate terminology. When changes in climatic conditions are discussed, it was requested that the actual climate variables (such as temperature, precipitation, length of growing season) that are being altered, be specified. Phrases such as 'changes in regional and global climate statistics' could also be used.

There is a very fundamental reason to limit the use of 'climate change' by the impacts community. Key societal and environmental resources, such as water, food, energy, ecosystem function, and human health respond to climate, not just to an incremental change in the climatic conditions. As noted earlier, the assumption of a stable climate system, in the absence of human intervention, is a mischaracterization of the behavior of the real climate system.

However, some authors retained the use of the terminology 'climate change'. It was acquiesced as long as there was a significant contribution in their chapter to a broad-based assessment of risk to the key resource they were discussing.

Another misused term is 'global change', when really what is almost always meant is a local and/or regional change in the environmental conditions, including from climate. The accurate terminology should be 'environmental change'. The term 'environmental change' is, therefore, preferred rather than 'global change', as the latter terminology is very much a top-down viewpoint. Almost all impacts on key resources are on the local and regional scale.

We also requested the authors start with the risks and factor in the climate threats after thresholds, etc. were first obtained. This was not done in some chapters, but this information can still be extracted from the text. Obtaining the spectrum of risks first is the more inclusive way to assess threats to key resources, and thus, in the view, to prepare the optimal mitigation and adaptation strategies.

For the climate component of risk, the outcome vulnerability (the top-down) approach relies on skillful weather predictions and analyzes with a regional and a local focus. For weather prediction on time periods of days to a week or two, excellent skillful predictions are available for use in outcome vulnerability assessments. On seasonal timescales, there is also some limited predictive skill to apply to outcome vulnerability assessments, particularly for such well-defined weather events such as an El Niño or La Niña (Castro et al. 2007). However, for decadal and multidecadal predictions little, if any, predictive skill has been shown in hindcast climate model predictions of changes in regional weather statistics beyond what is available to the impacts community via the historical, recent paleorecord and a worst case sequence of weather events.

To illustrate the lack of skill, the conclusions from several papers have been summarized. Fyfe et al. (2011) concluded that

> "….for longer term decadal hindcasts a linear trend correction may be required if the model does not reproduce long-term trends. For this reason, we correct for systematic long-term trend biases."

Xu and Yang (2012) find that without tuning from real world observations, the model predictions are in significant error. For example, they found that

> …the traditional dynamic downscaling (TDD) [i.e. without tuning) overestimates precipitation by 0.5-1.5 mm d-1…..The 2-year return level of summer daily maximum temperature simulated by the TDD is underestimated by 2-6°C over the central United States-Canada region."

The paper van Oldenborgh et al. (2012) report just limited predictive skill in two regions of the oceans on the decadal time period, but no regional skill elsewhere, when they conclude that:

> "A 4-model 12-member ensemble of 10-yr hindcasts has been analysed for skill in SST, 2m temperature and precipitation. The main source of skill in temperature is the trend, which is primarily forced by greenhouse gases and aerosols. This trend contributes almost everywhere to the skill. Variation in the global mean temperature around the trend does not have any skill beyond the first year. However, regionally there appears to be skill beyond the trend in the two areas of well-known low-frequency variability: SST in parts of the North Atlantic and Pacific Oceans is predicted better than persistence. A comparison with the CMIP3 ensemble shows that the skill in the northern North Atlantic and eastern Pacific is most likely due to the initialisation, whereas the skill in the subtropical North Atlantic and western North Pacific are probably due to the forcing."

Anagnostopoulos et al. (2010) report that

> "…. local projections do not correlate well with observed measurements. Furthermore, we found that the correlation at a large spatial scale, i.e. the contiguous USA, is worse than [even] at the local scale."

Stephens et al. (2010) wrote

> "models produce precipitation approximately twice as often as that observed and make rainfall far too lightly…..The differences in the character of model precipitation are systemic and have a number of important implications for modeling the coupled Earth system …….little skill in precipitation [is] calculated at individual grid points, and thus applications involving downscaling of grid point precipitation to yet even finer-scale resolution has little foundation and relevance to the real Earth system."

van Haren et al. (2012) concluded from their study with respect to climate model predictions of precipitation that

> "An investigation of precipitation trends in two multi-model ensembles including both global and regional climate models shows that these models fail to reproduce the observed trends….. A quantitative understanding of the causes of these trends is needed so that climate model based projections of future climate can be corrected for these precipitation trend biases…. To conclude, modeled atmospheric circulation and SST trends over the past century are significantly different from the observed ones."

Sun et al. (2012) found that

> "…in global climate models, [t]he radiation sampling error due to infrequent radiation calculations is investigated …….. It is found that…. errors are very large, exceeding 800 W m^{-2} at many non-radiation time steps due to ignoring the effects of clouds…."

There is an important summary of the limitations in multidecadal regional climate predictions in Kundzewicz and Stakhiv (2010) who succinctly conclude that

> "Simply put, the current suite of climate models were not developed to provide the level of accuracy required for adaptation-type analysis."

Since the top-down outcome vulnerability approach depends on skillful decadal and longer regional and local climate predictions, yet they have shown little if any skill, another approach is needed.

For this reason, the volume set of five books presents an alternate approach – the bottom-up, resource-based outcome (contextual) vulnerability perspective. The goal of the set was to focus on the climate component of stress but also consider, in-depth, other environmental and social threats.

The text of the articles is written at a level that allows undergraduate students to understand the material, while providing active researchers with a ready reference resource for information in the respective field.

The questions requested to the authors address with respect to a specific resource were:

1. Why is this resource important? How is it used? To what stakeholders is it valuable?
2. What are the key environmental and social variables that influence this resource?
3. What is the sensitivity of this resource to changes in each of these key variables? This includes, but is not limited to, the sensitivity of the resource to climate variations and change on short (e.g., days), medium (e.g., seasons), and long (e.g., multidecadal) timescales.
4. What changes (thresholds) in these key variables would have to occur to result in a negative (or positive) response to this resource?
5. What are the best estimates of the probabilities for these changes to occur? What tools are available to quantify the effect of these changes? Can these estimates be skillfully predicted?
6. What actions (adaptation/mitigation) can be undertaken in order to minimize or eliminate the negative consequences of these changes (or to optimize a positive response)?
7. What are specific recommendations for policymakers and other stakeholders?

There are also overview chapters that discuss the science of the resource.

Several authors insisted on focusing on the use of the outcome vulnerability (top-down) approach based on the multidecadal GCM projections (statistically or dynamically downscaled) as the starting point of their chapters. The chapters were accepted, despite this shortcoming, because when they finally discussed adaptation in their text, they did present the broader-based bottom-up focus that is the centerpiece of the volume. Readers,

however, need to be aware that the top-down, GCM scenarios are only a subset, at best, of what is plausible in the coming decades. Multidecadal predictions of changes in regional and local climate statistics have not shown skill when run in a hindcast mode for the past several decades.

In summary, the goal of the five-volume set of books is to document the value of a bottom-up, resource-based assessment of risk to key resources, as illustrated schematically in Figure 3a–e. Most, but not all, authors accepted this framework. This can be assessed without having any predictability on

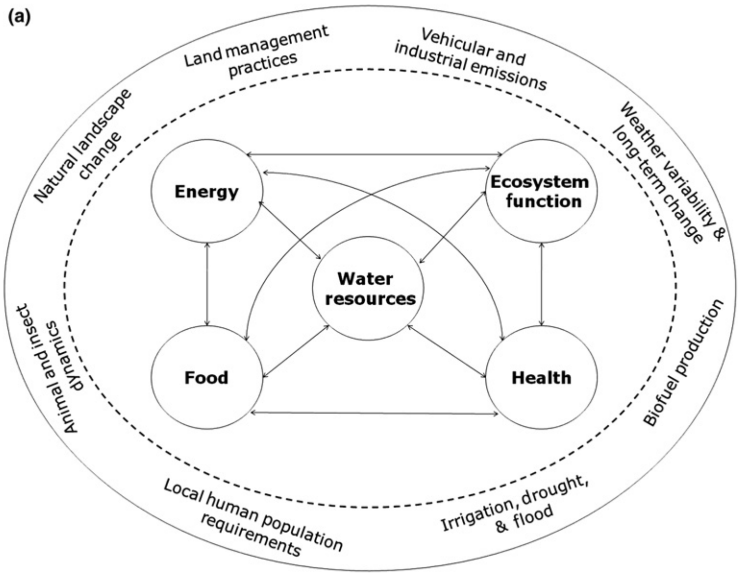
(a)
Land management practices
Vehicular and industrial emissions
Natural landscape change
Weather variability & long-term change
Energy
Ecosystem function
Water resources
Food
Health
Animal and insect dynamics
Biofuel production
Local human population requirements
Irrigation, drought, & flood

Figure 3a Contextual vulnerability for water resources (Hossain: Editor)

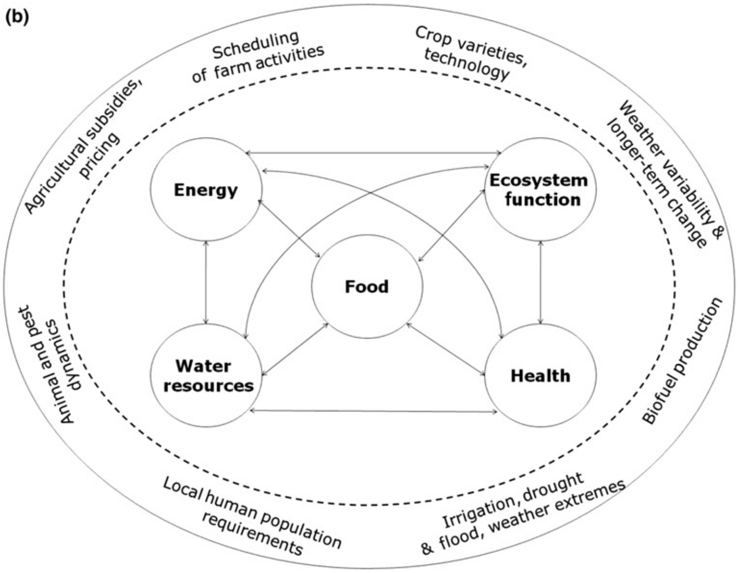
(b)
Scheduling of farm activities
Crop varieties, technology
Agricultural subsidies, pricing
Weather variability & longer-term change
Energy
Ecosystem function
Food
Water resources
Health
Animal and pest dynamics
Biofuel production
Local human population requirements
Irrigation, drought & flood, weather extremes

Figure 3b Contextual vulnerability for food (Niyogi: Editor).

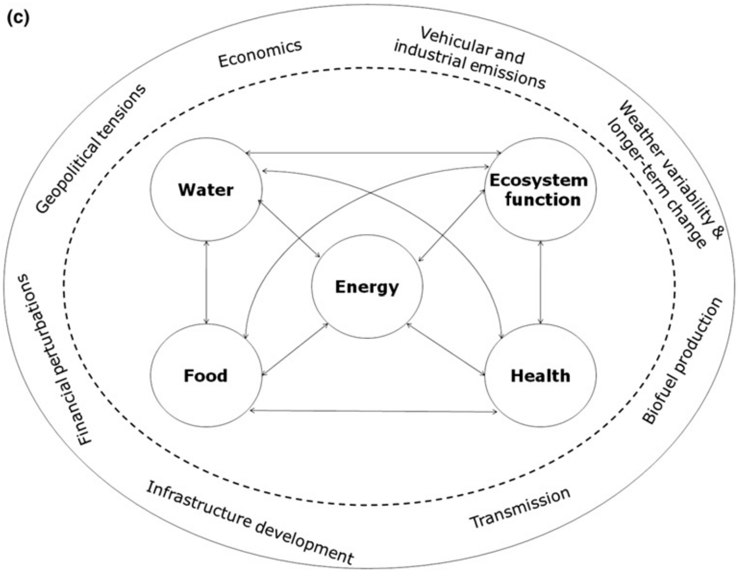
(c)
Economics
Vehicular and industrial emissions
Geopolitical tensions
Weather variability & longer-term change
Water
Ecosystem function
Energy
Food
Health
Financial perturbations
Biofuel production
Infrastructure development
Transmission

Figure 3c Contextual vulnerability for energy (Kallos: Editor).

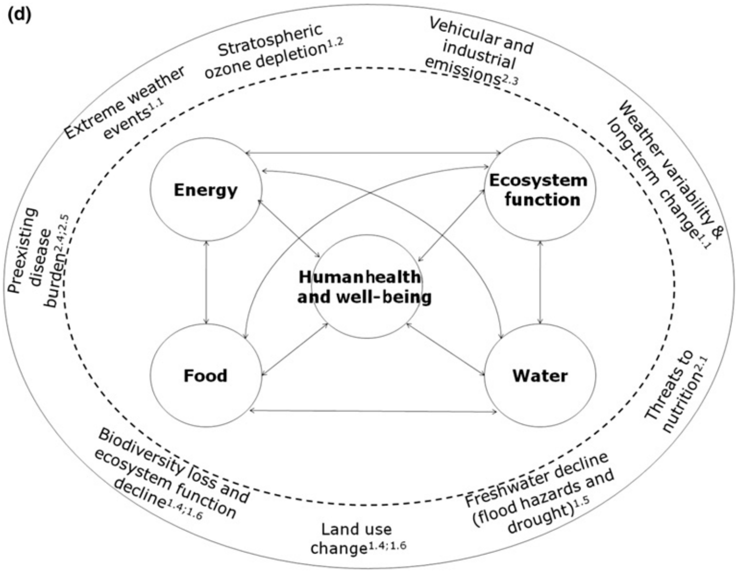
(d)
Stratospheric ozone depletion1.2
Vehicular and industrial emissions2.3
Extreme weather events1.1
Weather variability & long-term change1.1
Energy
Ecosystem function
Preexisting disease burden2.4;2.5
Humanhealth and well-being
Food
Water
Threats to nutrition2.1
Biodiversity loss and ecosystem function decline1.4;1.6
Land use change1.4;1.6
Freshwater decline (flood hazards and drought)1.5

Figure 3d Contextual vulnerability for human health and well-being (Adegoke and Wright Editors).

multidecadal time periods. It is an alternative (and more inclusive) perspective than the IPCC top-down outcome vulnerability approach which starts with the GCMs as the overarching framework. In the bottom-up approach, the scenarios from the GCM predictions should only enter after the specific threats to the resources are determined and even then, they provide, at best, a limited set of insights into what is possible.

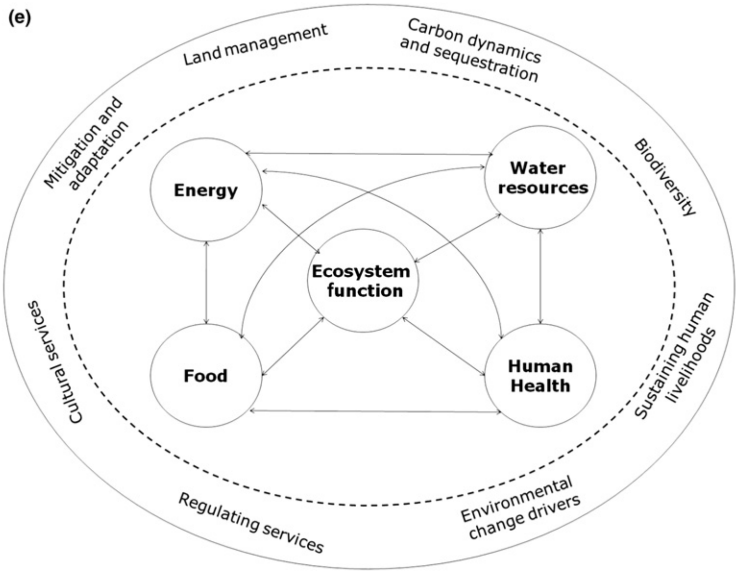
(e)
Land management
Carbon dynamics and sequestration
Biodiversity
Sustaining human livelihoods
Environmental change drivers
Regulating services
Cultural services
Mitigation and adaptation
Energy
Water resources
Ecosystem function
Food
Human Health

Figure 3e Contextual vulnerability for ecosystem function (Seastedt and Suding; Editors).

We look forward to feedback from the readers.

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Jimmy Adegoke,
Faisal Hossain,
George Kallos,
Dev Niyogi,
Timothy Seastedt,
Katharine Suding,
Caradee Y. Wright and
Dallas Staley

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Preface - Vulnerability of Ecosystems to Climate

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Ecologists tend to focus on local and regional phenomena. Our ability to experiment on complex ecological systems usually means that we work at small spatial scales. Such an approach has resulted in our contention that local ecological systems have very large effects on the outcome of experiments involving environmental change drivers across the Earth such as those described below. The last few years have seen an explosion of studies documenting how human influences on the climate system will affect both natural and human-dominated ecosystems. Thus, when Roger Pielke Sr. asked us to become involved in a 'bottom-up approach' to dealing with the vulnerability of ecosystems to climate, we looked at this assignment with interest as a learning opportunity.

Environmental change factors are common and numerous, and many of these might be viewed as orthogonal or independent of changes in climate. Human-driven land use change, fragmentation, wildfires, increases in atmospheric nitrogen content, or increases in atmospheric pollutants, and so on have been ongoing for millennia, but these factors have intensified during the explosion of the human population over the last decades. As stated so succinctly by authors in this volume, changes associated with human population growth and resource use are first-order factors driving environmental changes, and these changes will be ongoing and in many cases intensifying during the coming decades.

A bottom-up perspective can mean several things: appreciating multiple climate forcings, appreciating that social and ecological interactions can influence response to these forcings, and appreciating that these forcings depend on other environmental change factors. Different authors emphasize different aspects of this bottom-up approach depending on the topic and expertise, but all bring home the point that we are dealing with complex systems in which vulnerability and sustainability require a broad and multifaceted approach. The current 'state of the environment' is generated by interaction effects and feedbacks, and rarely is the environmental status controlled by a single variable such as warming of the planet. Unfortunately, many people translate complexity and the inability to identify single factors as causal agents as 'uncertainty.' There is plenty of uncertainty out there; however, we are quite certain about the importance of the interactions among environmental change factors and have substantial knowledge of many of their combined effects and impacts. In order for ecosystem stewardship to be successful, we must embrace this complexity and not let uncertainty be an excuse for inaction.

What we are not certain about, given the complexity and nonlinearity of the interactions, are future conditions. The future will be created by decisions and actions yet to be determined as well as from incompletely understood behavior of the natural system. The future, when viewed at local, regional, and global scales, is somewhere between rosy and apocalyptic. Stakeholders don't get to choose the outcome, but their current decisions about abiotic and biotic resources contribute to this outcome. Although we have no crystal ball, the logic of pursuing 'win–win' decisions now that will contribute to the sustainability of urban to natural ecosystems is compelling and can move the outcome in ways that are beneficial to society.

Our goals are similar to companion volumes focusing on water, human health, agriculture, and energy. In the context of interactions and complexity in the current era of environmental change, we asked the authors to address:

- *What are the key issues or threats facing ecosystem processes and ecosystem services today?*
- *How do we use the understanding of these issues to increase resilience and sustainability in the near future?*

Because the 'near future' is a key focus, it avoids assessments based purely on the commonly studied 50 or 100 year emission-driven scenarios of future climate. The more pressing question for local stakeholders is:

- *What do we need to do right now so that we can do an even better job of ecosystem stewardship in the future?*

We are pleased to be able to draw on the breadth of knowledge about ecosystems and environmental change by bringing together chapters composed by a wide range of eminent scientists investigating aspects of the local drivers, responses, and feedbacks critical to understanding the complexity and nonlinearity of systems in the future. Biogeochemists, ecologists, anthropologist, and economists have weighed in on the topic. The chapters reflect this interdisciplinary and broad approach to sustainability and vulnerability: some highly quantitative, others more qualitative, some very place-based, others seeking more general phenomena. This diversity in approaches reflects the importance of multiple pathways toward knowledge generation; indeed, as Terry Chapin points out in the introductory chapter, sustainability and well-being are value-based normative concepts seen through many frames by a diverse set of stakeholders. Because their assessment is as much a political as a scientific process across a large diverse set of stakeholders, we need this diversity in order to effectively link vulnerability analyses to decision making.

We have organized this book to provide three types of perspectives in considering vulnerability: from threats to ecosystems and their services (Section 1, Chapters 2–7), from focal ecosystem processes and services (Section 2, Chapters 8–14), and from place-based or specific system assessments (Section 3, Chapters 15–25). The volume ends with a focus on planning, mitigation, and adaptation strategies. We are delighted by the many linkages among the different perspectives, in part reflecting that no one approach will be a silver bullet to address these issues.

Where do we go from here? The phrase, 'think globally, act locally,' attributed to Patrick Geddes in 1915 continues to resonate a century later. However, the point of this volume and others in this series is that by acting locally, one not only can change the world, but also can mitigate some of what the world is going to throw at us. Moreover, as each locality will get thrown a different set of challenges, we cannot expect one-size-fits all solutions. Ecosystem stewardship will need to reflect this place-based context.

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4.01 Overview of Ecosystem Functions and Services: Their Importance and Vulnerability

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4.01.1 Introduction

The world is undergoing unprecedented changes in many of the factors that determine both its fundamental properties and their influence on society. Throughout human history, people have interacted with and shaped ecosystems for social and economic development (Turner et al. 1990; Redman 1999; Jackson 2001; Diamond 2005). During the last 50 years, however, human activities have changed ecosystems more rapidly and extensively than at any comparable period of human history (Steffen et al. 2004; Foley et al. 2005; MEA 2005). Regions of the Earth's climate for example, are now warmer than at any time in the last 500 (and probably the last 1300) years (IPCC 2007), in part because of atmospheric accumulation of carbon dioxide (CO_2) released by the burning of fossil fuels (**Figure 1**). Agricultural development largely accounts for the accumulation of other trace gases that contribute to further changes in the composition of the Earth's atmosphere (Foley et al. 2011). As the human population increases, an increased demand for food and natural resources has led to an expansion of agriculture, forestry, and other human activities, causing large-scale land-cover change and loss of habitats and biological diversity. Approximately half the world's population now lives in cities and depends on connections with rural areas worldwide for food, water, and waste processing. In addition, increased human mobility is spreading plants, animals, diseases, industrial products, and cultural perspectives more rapidly than ever before. This increase in global mobility, coupled with increased connectivity through global markets and new forms of communication, links the world's economies and cultures, so decisions in one place often have international consequences.

This globalization of economy, culture, and ecology is important, because it modifies the life-support system of the planet (Odum 1989), that is, the capacity of the planet to meet the needs of all organisms, including people. The dramatic increase in the extinction rate of species (100–1000-fold in the last two centuries) indicates that global changes have been catastrophic for many species, although some species, especially invasive species and some disease organisms, have benefited and expanded their ranges (Mace et al. 2005).

The unique feature of the changes described above is that they are directional. In other words, they show a persistent trend over time (**Figure 1**). Many of these trends have become more pronounced since the mid-twentieth century and will probably continue or accelerate in the coming decades, even if society takes concerted actions to reduce some rates of change. This situation creates a dilemma in planning for the future, because we cannot assume that the future world will behave as we have in the past or that our past experience provides an adequate basis to plan for the future. We must adopt a more flexible approach to managing ecosystems – management to sustain the functional properties of ecosystems that are important to society, under conditions where the system itself is constantly changing.

Changes in the Earth System are highly interconnected. None of the changes mentioned above are purely physical, ecological, or social. Therefore, understanding current and future change requires a broad interdisciplinary framework that draws on the concepts and approaches of many natural and social sciences. We must understand the world, region, or community as a social-ecological system in which people depend on resources and services provided by ecosystems. Ecosystem dynamics are influenced, to varying degrees, by human activities (Berks et al. 2003; Turner et al. 2003; Steffen et al. 2004). Although the relative importance of social and ecological processes may vary from forests to farms to cities, the functioning of each of these systems, and of the larger

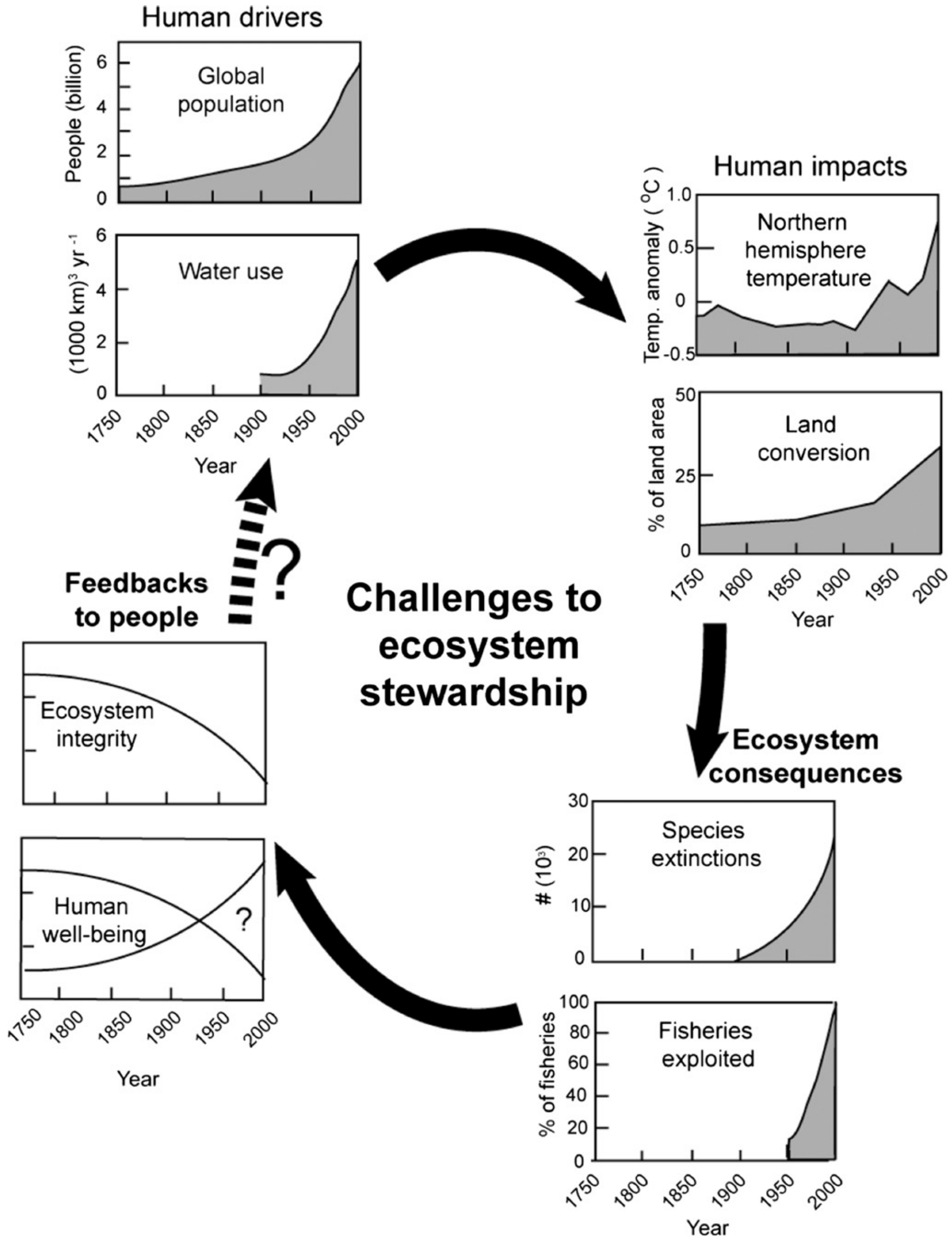

Figure 1 Challenges to ecosystem management and stewardship. Changes in human population and resource consumption alter climate and land cover, which have important ecosystem consequences such as species extinctions and over-exploitation of fisheries. These changes reduce ecosystem integrity and have regionally variable effects on well-being, which feed back to further changes in human drivers. Redrawn from Chapin III, F. S., G. P. Kofinas, and C. Folke, Eds., 2009: *Principles of Ecosystem Stewardship: Resilience-Based Natural Resource Management in a Changing World*. Springer, New York with panels from Steffen, W. L., A. Sanderson, P. D. Tyson, J. Jäger, P. A. Matson, et al., 2004: *Global Change and the Earth System: A Planet under Pressure*. Springer-Verlag, New York.

regional system in which they are embedded, is strongly influenced by physical, ecological, economic, and cultural factors. Therefore, they are best viewed, not as ecological or social systems, but as social–ecological systems that reflect the interactions of physical, ecological, and social processes (Figure 2).

In studying the response of social–ecological systems to directional change, we pay particular attention to the processes that link ecological and social components (Figure 2). The environment affects people through environmental events, the direct effects of physical processes such as floods and droughts, and ecosystem services, and the benefits that people derive

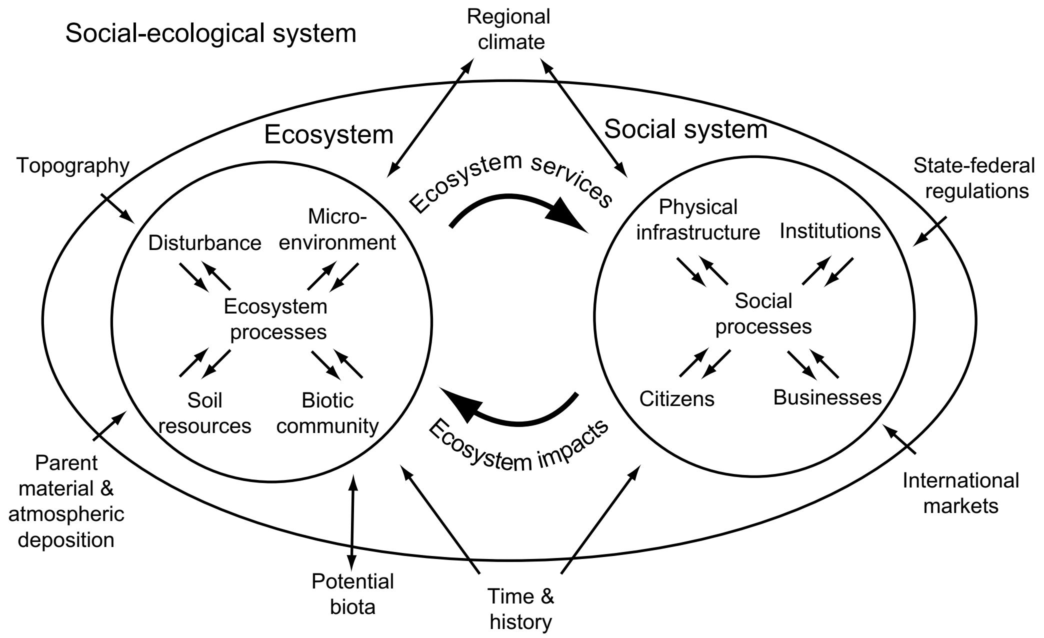

Figure 2 Controls over the functioning of social–ecological systems. Human impacts on ecosystems are mediated by a variety of social processes, and society benefits from the services provided by ecosystems. Modified from Whiteman, G., B. C. Forbes, J. Niemelä, and F. S. Chapin, III, 2004: Bringing feedback and resilience of high-latitude ecosystems into the corporate boardroom. *Ambio*, **33**, 371–376.

from ecosystems. Society in turn affects ecosystems through the impacts of human activities.

4.01.2 Vulnerability, Resilience, Sustainability, and Stewardship of Ecosystem Services

Given the rapid global changes that are occurring, it is important to consider rigorously the vulnerability, resilience, sustainability and stewardship associated with changes in ecosystems. We introduce each of these concepts in this section.

4.01.2.1 Vulnerability

Vulnerability is the degree to which a system is likely to experience harm due to exposure to a specified hazard or stress (Turner et al. 2003; Adger 2006). Vulnerability theory is rooted in socio-economic studies of impacts of events (e.g., floods or wars), or stresses (e.g., chronic food insecurity) on social systems, but has been broadened to address responses of ecosystems and entire social–ecological systems. Vulnerability analysis deliberately addresses human values, such as equity and well-being. Vulnerability to a given stress can be reduced by (1) reducing exposure to the stress (mitigation); (2) reducing sensitivity of the system to stress by sustaining ecological integrity and the components of human well-being; and/or (3) increasing adaptive capacity and resilience (see below) to cope with stress (Turner et al. 2003).

Exposure to a stress can be reduced by minimizing its intensity, frequency, duration, or extent. Prevention of pollution or banning of toxic pesticides, for example, reduces the vulnerability of people who would otherwise be exposed to these hazards. Mitigation (reduced exposure) is especially challenging when the stress is the cumulative effect of processes occurring at scales that are larger than the system being managed. Anthropogenic contributions to climate change through the burning of fossil fuels, for example, is globally dispersed, so it cannot be reversed by actions taken solely by those regions that experience the greatest impacts of climatic change (McCarthy et al. 2005). Other globally or regionally dispersed stresses include inadequate supplies of clean water and uncertain availability of nutritious food (Steffen et al. 2004; Kasperson et al. 2005).

Sensitivity to a stress can be reduced in at least three ways: (1) sustaining the slowly changing ecological variables that determine natural capital (i.e., the natural resources that support the functioning of ecosystems); (2) maintaining key components of well-being; and (3) paying particular attention to the needs of the disadvantaged segments of society, who are generally most vulnerable. The poor or disadvantaged, for example, are especially vulnerable to food shortages or economic downturns, and people living in floodplains or the wildland–urban interface are especially vulnerable to flooding or wildfire, respectively. An understanding of the causes of differential vulnerability can lead to strategies for targeted interventions to reduce overall vulnerability of the social–ecological system.

4.01.2.2 Resilience

Resilience is the capacity of a social–ecological system to absorb a spectrum of shocks or perturbations, and to sustain and develop its fundamental function, structure, identity, and feedbacks through either recovery or reorganization in a new context (Holling 1973; Gunderson and Holling 2002; Walker et al. 2004; Folke 2006). In a sense, it is the flexibility of the system to adjust to shocks and surprises. Resilience depends on

(1) the capacity of individual species or components of the system to adapt; (2) biophysical and social legacies that contribute to diversity and provide proven pathways for rebuilding; (3) the capacity of people to plan for the long term within the context of uncertainty and change; (4) a balance between stabilizing feedbacks that buffer the system against stresses, disturbance, and innovation that creates opportunities for change; and (5) the capacity to adjust governance structures to meet changing needs (Holling and Gunderson 2002; Folke et al. 2003; Walker et al. 2006). Loss of resilience pushes a system closer to its limits. When resilience has been eroded, a disturbance like a disease, storm, or market fluctuation, that previously shook and revitalized the resilient system, might now push the fragile system over a threshold into an alternative state with a new trajectory of change. Such system changes radically alter the flow of ecosystem services, associated livelihoods, and well-being of people and societies.

Sources of diversity, which is essential for adaptation, are critical to resilience. Fostering small-scale variability and change logically contributes to resilience, because it maintains within the system those components that are well adapted to each phase of the cycles of ecosystem disturbance and recovery. This reduces the likelihood that the inevitable disturbances will have catastrophic effects. Conversely, preventing small-scale disturbances such as insect outbreaks or fires tends to eliminate disturbance-adapted components, thereby reducing the capacity of the system to cope with disturbance.

4.01.2.3 Sustainability

Sustaining the desirable features of our current world for future generations is an important societal goal. The challenge of doing so in the face of persistent directional trends in underlying controls has led to an emerging science of sustainability (Clark and Dickson 2003). In this book we use the United Nations Environment Programme's definition of sustainability: the use of the environment and resources to meet the needs of the present without compromising the ability of future generations to meet their own needs (WCED 1987). According to this definition, sustainability requires that people be able to meet their own needs, that is, to sustain human well-being now and in the future (Dasgupta 2001). Since sustainability and well-being are value-based concepts, there are often conflicting visions about what should be sustained and how sustainability should be achieved. Thus, the assessment of sustainability is as much a political as a scientific process, and requires careful attention to whose visions of sustainability are being addressed (Shindler and Cramer 1999). Nonetheless, any vision of sustainability ultimately depends on the life-support capacity of the environment and the generation of ecosystem services.

4.01.2.4 Stewardship

Given the challenges of sustainable use of ecosystems during times of rapid change, a hands-off approach to managing ecosystems is no longer sufficient to sustain ecosystem services and the needs of society. Ecosystem stewardship is the shaping of trajectories of social–ecological change to sustain ecosystem resilience and human well-being. Stewardship is challenging because we are often uncertain about future trajectories of change. However, uncertainty has always characterized social–ecological systems and should therefore not be an excuse for inaction. Stewardship inevitably entails tradeoffs, particularly between efficiency and flexibility and between immediate and long-term benefits (Kareiva et al. 2007; Chapin et al. 2009).

Ecosystem stewardship integrates three broadly overlapping sustainability approaches (Figure 3): reducing vulnerability to expected changes; fostering resilience to sustain desirable conditions in the face of perturbations and uncertainty; and transforming from undesirable trajectories when opportunities emerge. The need is to identify pragmatic strategies that increase the likelihood of socially beneficial outcomes and reduce the risk of bad outcomes. This approach is explicitly focused on human norms, values, and well-being and must therefore continually be debated and reassessed by stakeholders.

4.01.2.5 Ecosystem Services

Ecosystem services are the benefits that society receives from ecosystems. They provide a pragmatic framework for managing ecological sustainability. Ecosystems provide well-recognized provisioning services (goods), including water, timber, forage, fuels, medicines, and precursors to industrial products that are harvested from ecosystems. Ecosystems also provide regulatory services such as recycling of water and chemicals, mitigation of floods, pollination of crops, and cleansing of the atmosphere, as well as cultural services that meet recreational, aesthetic, and spiritual needs (Figure 4; Daily 1997; MEA 2005). All of these services depend on ecosystem processes that are sometimes known as supporting services. These processes include biogeochemical cycles, diversity maintenance, and disturbance cycles. Unless these underlying ecosystem properties are maintained, other services that are more directly recognized and valued by society cannot be sustained.

The overuse or misuse of resources can alter the functioning of ecosystems and the services they provide. Land-use change, for example, can degrade the capacity of watersheds to purify water, leading to large water treatment costs to cities (Grove 2009). Degradation and loss of wetlands can expose communities to increased damage from floods and storm surges (Kates et al. 2006). Decimation of populations of insect pollinators has reduced yields of many crops (Ricketts et al. 2004). Human caused introductions and invasions of non-native species such as killer bees, fire ants, and zebra mussels, cause enormous damage to living resources and threaten human health (Patz et al. 2005; Díaz et al. 2006). Human activities also indirectly affect ecosystem goods and services through changes in the atmosphere, hydrologic systems, and climate.

Management decisions often involve choices that reflect tradeoffs among ecosystem services. Forest harvest, for example, yields forest products at the expense of recreational opportunities provided by the uncut forest. Policies that enhance recreational values to snow machine users may diminish their value to cross-country skiers. Deforestation of tropical forests may provide local users with both forest products and land to support agriculture, but degrade soils in ways that diminish the livelihood opportunities for future generations. An important step in ecosystem management is to

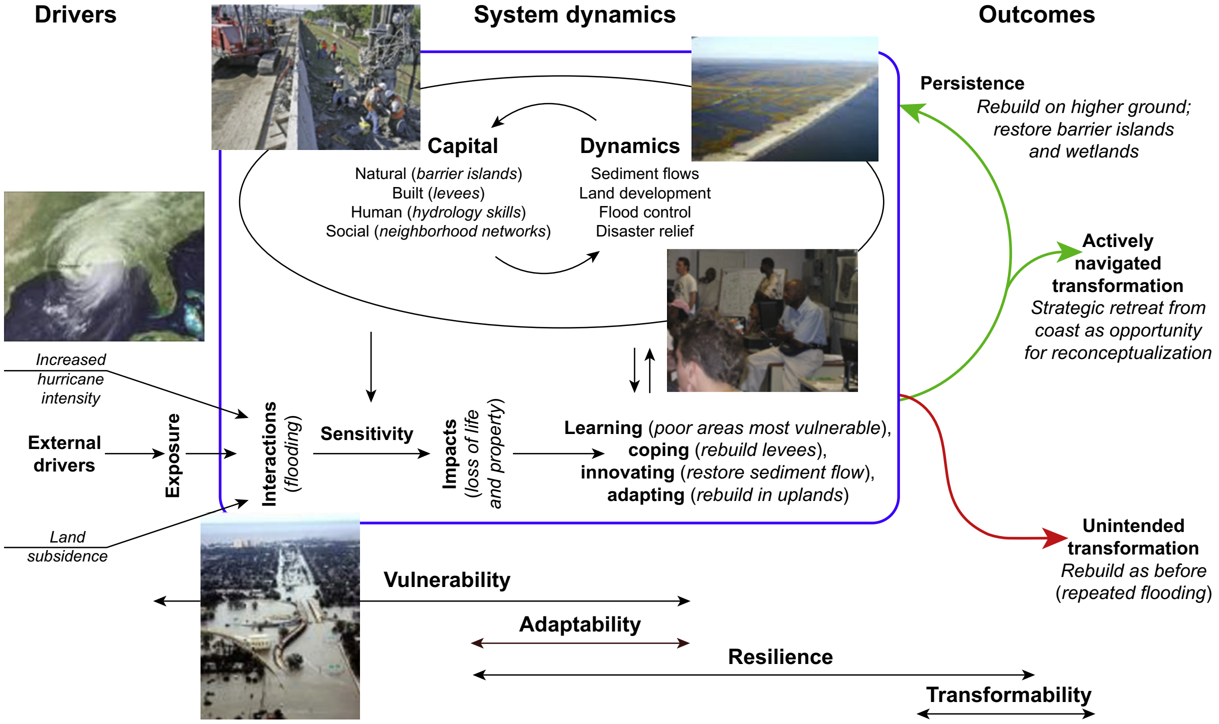
Drivers
System dynamics
Outcomes
Capital
Natural (barrier islands)
Built (levees)
Human (hydrology skills)
Social (neighborhood networks)
Dynamics
Sediment flows
Land development
Flood control
Disaster relief
Persistence
Rebuild on higher ground; restore barrier islands and wetlands
Actively navigated transformation
Strategic retreat from coast as opportunity for reconceptualization
Increased hurricane intensity
External drivers
Exposure
Interactions (flooding)
Sensitivity
Impacts (loss of life and property)
Learning (poor areas most vulnerable),
coping (rebuild levees),
innovating (restore sediment flow),
adapting (rebuild in uplands)
Land subsidence
Unintended transformation
Rebuild as before (repeated flooding)
Vulnerability
Adaptability
Resilience
Transformability

Figure 3 Application of the ecosystem stewardship framework to the impact and response of New Orleans to Hurricane Katrina. A suite of external stresses (land subsidence from wetland drainage and increased hurricane intensity associated with warming) interact to create impacts (loss of life and property). Social learning (learning, coping, innovating, and adapting) in response to these impacts has the potential to alter social–ecological interactions and various forms of capital of the system (New Orleans, the blue box), which in turn influence sensitivity to future events. Social learning also governs the relative likelihood of three potential outcomes: persistence of the existing system through resilience; actively navigated transformation to a new, potentially more beneficial trajectory through transformation; or unintended degradation to a new state due to vulnerability and failure to adapt or transform. Reprinted from Chapin, F. S., III, S. R. Carpenter, G. P. Kofinas, C. Folke, N. Abel, et al., 2010: Ecosystem stewardship: sustainability strategies for a rapidly changing planet. *Trend. Ecol. Evol.*, **25**, 241–249.

assess potential impacts of decisions on multiple ecosystem services. This is challenging, given the huge number of services provided by ecosystems and uncertainties in their responses to a particular action. It is often pragmatic to focus particularly on a few critical ecosystem services, those services that are most vulnerable to change, have fewest options for technological or ecological substitution, and are most valued by society (A. Kinzig, 2012, pers. comm.).

4.01.3 Supporting Services: Sustaining Ecosystem Functioning

Supporting services are the fundamental ecological processes that control the structure and functioning of ecosystems. Managers and the public often overlook these services because they are not the products directly valued by society. Moreover, they are frequently controlled by slow variables (i.e., variables that change relatively slowly) and are therefore taken for granted by agencies tasked with managing particular ecosystem goods such as trees or fish. However, because of the fundamental dependence of all ecosystem services on supporting services, integrity of these services generally sustains many services that are valued more directly by society. This section focuses on the slow variables that most frequently control ecosystem processes, and therefore, a broad suite of ecosystem services.

4.01.3.1 Maintenance of Soil Resources

Soils and sediments are key slow variables that regulate ecosystem processes by providing resources required by organisms. The controls over the formation, degradation, and resource-supplying potential of soils and sediments are therefore central to sustaining the natural capital on which society depends (Birkeland 1999; Chapin et al. 2011). The quantity of soil in an ecosystem depends largely on the balance between inputs from weathering (the breakdown of rocks to form soil), or deposition and losses from erosion. In addition, organisms, especially plants, add organic matter to soils through death of tissues and individuals, which is offset by losses through decomposition. If an ecosystem were at a steady state (i.e., when inputs approximately equal outputs), then the quantity of soil would remain relatively constant, providing a stable capacity to supply vegetation with water and nutrients. Natural imbalances between inputs and outputs lead to deeper soils in floodplains and at the base of hills than on hilltops. When averaged over large regions, however, changes in soil capital due to imbalances between inputs and outputs usually occur slowly (approximately 0.1–10 mm per century) (Selby 1993). In general, the presence of a plant canopy and litter layer (the layer of dead leaves on the soil surface) reduces erosion. Human activities that reduce vegetation cover can increase erosion rates by several orders of magnitude, just as occurs naturally when glaciers,

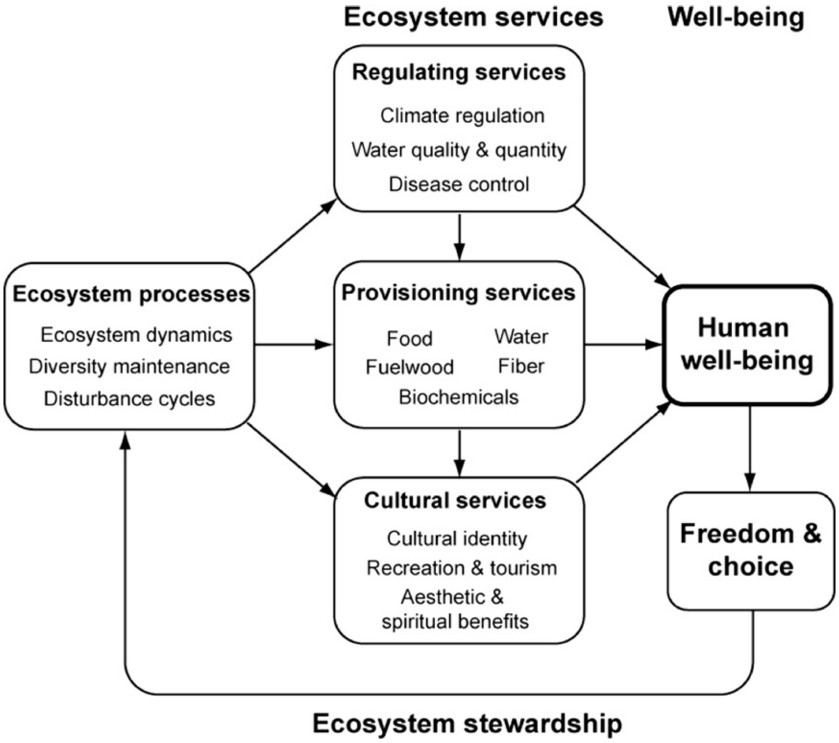

Figure 4 Linkages among ecosystem processes, ecosystem services, and the well-being of society, a framework developed by the Millennium Ecosystem Assessment (MEA 2005). Ecosystem processes are the foundation for ecosystem services that are directly used by society and which strongly influence human well-being. Human actions influence the life-support system of the planet through effects on environment (e.g., climate) and on ecosystems. Redrawn from Chapin, F. S., III, 2009: Managing ecosystems sustainably: the key role of resilience. F. S. Chapin, III, G. P. Kofinas, and C. Folke, Eds., *Principles of Ecosystem Stewardship: Resilience-Based Natural Resource Management in a Changing World*. Springer, New York, 29–53.

volcanoes, or landslides reduce vegetation cover. Under these circumstances, ecosystems can lose soils within a period of years to decades that may have required thousands of years to accumulate, causing an essentially permanent loss of the productive capacity of ecosystems. Similarly, human modification of river channels can alter sediment inputs.

4.01.3.2 Water Cycling

Water is the soil resource which is used in the largest quantities by plants and which most frequently limits the productivity of terrestrial ecosystems. Water enters ecosystems as precipitation. Two of the major pathways of water loss are transpiration, the 'green water' that supports terrestrial production, and runoff, which replenishes groundwater and aquatic ecosystems, the 'blue water' sources that are often tapped by people for domestic and industrial uses, irrigation, and hydropower. Consequently, there are inherent tradeoffs among the ecosystem services provided by water cycling, and some of the biggest challenges in water management result from these tradeoffs.

Climatic controls over precipitation place an ultimate constraint on quantities of water cycled through ecosystems. Within this constraint, the partitioning of water between transpiration and runoff depends on (1) the degree of compaction of the soil surface, which influences water infiltration into the soil, (2) soil water-holding capacity, which depends on the quantity of soil and its particle-size distribution, and (3) the capacity of vegetation to transpire water (Rockström et al. 1999).

Vegetation fosters infiltration and storage through several mechanisms. The plant canopy and litter reduce compaction by raindrops that otherwise tend to seal soil pores. In addition, roots and soil animals associated with vegetation create channels for water movement through the soil profile. By facilitating water infiltration (due to reduced compaction), water-holding capacity (due to production of soil organic matter), and reduced soil erosion (due to reduced overland flow), vegetation generates stabilizing feedbacks that sustain the productive potential of soils and reduce ecosystem vulnerability to drought (Bruijnzeel 2004; Uriarte et al. 2011). Human activities often disrupt these stabilizing feedbacks, thereby reducing resilience. For example, high densities of livestock or movement of heavy farm machinery at times (spring) or places (riparian corridors) where soils are wet can compact soils and reduce infiltration. Plowing reduces soil organic content substantially – often by 50% within a few years – thereby reducing soil water-holding capacity and the capacity of soils to support crop growth with natural rainfall (Matson et al. 1997). Alternative agricultural practices that conserve or rebuild soil organic content (e.g., no-till agriculture) or reduce compaction by livestock or equipment under wet conditions increase the capacity of soils to supply water to crops or other vegetation.

Transpiration is tightly linked to the capacity of plants to fix carbon and therefore to their productive potential. This explains why productive agricultural systems are such prodigious consumers of water and why streamflow increases after logging. At a more subtle level, any factor that increases the productive potential of vegetation (e.g., nutrient additions from fertilizers, introduction of exotic nitrogen-fixing species; atmospheric deposition of nitrogen; replacement of shrublands by forests) will increase transpiration (green water flows) and reduce water movement to groundwater and runoff (blue water flows). The tradeoffs between transpiration and runoff have implications for the role of ecosystems in regulating water flow (Jones et al. 2012).

4.01.3.3 Carbon and Nutrient Cycling

Within a climate zone, the availabilities of belowground resources (water and nutrients) are the main factors that constrain terrestrial carbon cycling and ecosystem productivity. The carbon, nutrient, and water cycles of terrestrial ecosystems are tightly linked. The major controls are (1) climate, which governs water inputs, rates of soil development, and cycling rates of carbon, nutrients, and water; (2) the water- and nutrient-holding capacity of soils, which depends on particle size and organic content; and (3) the productive capacity of vegetation (Hobbie 1996; Jobbagy and Jackson 2000; De Deyn et al. 2008) In addition, carbon and nutrient cycles are physically linked because carbon forms the skeleton of organic compounds that carry nitrogen and phosphorus among plants, animals, and soils.

4.01.3.4 Maintenance of Biological Diversity

The known effects of biodiversity on ecosystem functioning relate most strongly to traits that govern the effect of species on ecosystem processes and traits that govern the response of species to environmental variation. These known effects of biodiversity change (both loss of key species or invasion of species with large impacts) can be buffered by maintaining species that span the spectrum of effect diversity and response diversity present in the system (Elmqvist et al. 2003; Suding et al. 2008).

Keystone species are species that have disproportionately large effects on ecosystems, typically because they alter critical slow variables. Ecosystems are most likely to sustain their current properties if current keystone species (or their functional equivalents) are maintained, and new ones are not introduced. Species that influence the supply of growth-limiting resources generally have large effects on the functioning of ecosystems. *Morella faya*, for example, is a nitrogen-fixing tree introduced to nitrogen-poor ecosystems of Hawaii by the Polynesians. The resulting increases in nitrogen inputs, productivity, and canopy shading eliminated many plant species from the formerly diverse understory of this forest (Vitousek 2004). Highly mobile animals, such as salmon and sheep, act as keystone species governing nutrient supply by feeding in one place and dying or defecating somewhere else. Similarly, species that modify disturbance regime exert strong effects on ecosystem functioning through their effects on cycles of disturbance and recovery. The introduction of flammable grasses into a tropical forest, for example, can increase fire frequency and trigger a regime shift from forest to savanna (D'Antonio and Vitousek 1992). One of the main ways that animals affect ecosystem processes is through physical disturbance (Jones et al. 1994). Gophers, pigs, and ants, for example, disturb the soil, creating sites for seedling establishment and favoring early successional species. Elephants trample vegetation and remove portions of tree canopies, altering the competitive balance between trees and grasses in tropical savannas. Many keystone species exert their effect by modifying species interactions, for example by eating other species (e.g., forest pests) or competing or facilitating the growth of other species (Chapin et al. 2000). Conserving key functional types (i.e., a group of species that have similar effects on ecosystem processes) and preventing the invasion of novel functional types reduces the likelihood of large changes in ecosystem services.

Diversity in the environmental response of species can stabilize ecosystem processes. Many species in a community appear functionally similar, for example, algal species in a lake or canopy trees in a tropical forest (Scheffer and van Nes 2004). What are the ecosystem consequences of changes in diversity within a functional type (i.e., functional redundancy)? Differences in environmental responses among functionally similar species provide resilience by stabilizing rates of ecosystem processes (McNaughton 1977; Chapin and Shaver 1985). In mid-latitude grasslands, for example, cool season grasses are particularly productive under cool, moist conditions, and warm season grasses under hot, dry conditions. As environmental conditions fluctuate within and among years, different species attain a competitive advantage over other functionally similar species (i.e., other grasses), thus stabilizing rates of ecosystem processes of the entire community (Ives et al. 1999).

The functional redundancy associated with species diversity also provides insurance against more drastic changes in environment, such as those that may occur in the event of human mismanagement of ecosystems or change in climate. Radical changes in environment are unlikely to eliminate all species of a given functional type in a diverse ecosystem, allowing the surviving species to increase in abundance and maintain functions that might otherwise be seriously compromised. Overgrazing in Australian grasslands, for example, eliminated the dominant species of palatable grass, severely reducing the quantity of cattle that the ecosystem could support and exposing the soil to wind erosion. Fortunately, a previously rare grass species that was less palatable, survived the overgrazing and increased in abundance, when the dominant grass declined, thus maintaining grass cover and reducing potential degradation from erosion (Walker et al. 1999). These examples of diversity effects on resilience provide hints of the general importance of diversity in stabilizing ecosystem processes and associated ecosystem services and suggest that management that sustains diversity is critical to long-term sustainability.

4.01.3.5 Maintenance of Disturbance Regime

Disturbance shapes the long-term fluctuations in the structure and functioning of ecosystems, and therefore, their resilience and vulnerability to change. Disturbances are relatively discrete events that alter ecosystem structure and cause changes in resource availability or physical environment (Pickett and White 1985). Natural Disturbance is not something that 'happens' to ecosystems, but is an integral part of their functioning. Species are typically adapted to the disturbance regime (i.e., the characteristic severity, frequency, type, size, timing, and intensity of disturbance) that shaped their evolutionary histories. Grassland and boreal species, for example, resprout rapidly after fire or have reproductive strategies that enable them to colonize recent burns (Johnson 1992). In contrast, many tropical tree species produce a pool of young seedlings that grow slowly in the understory, 'waiting' until a hurricane or other event creates gaps in the canopy (Chazdon 2003). The tropical tree strategy is poorly adapted to fire, which would kill the understory seedlings, and the boreal trees are poorly adapted to wind, which would leave an organic seedbed unfavorable for post-

disturbance germination. Naturally occurring disturbances such as fires and hurricanes are therefore not 'bad'; they are normal properties of ecosystems and indeed are essential for the long-term resilience of species and community dynamics that characterize a particular ecosystem (Dale et al. 2001).

4.01.4 Ecosystem Stewardship and Sustainability: Where and When Will Ecosystem Services Be Most Vulnerable?

Seeking to skillfully forecast how an ecosystem could respond to future conditions is a daunting, but critical, task necessary to achieve sustainability. We do not expect systems to act uniformly in their vulnerability and resilience, and we do not expect that responses will always be gradual and uniform. A grand challenge will be to assess the predictability of both the nature (what systems, what attributes of these systems, what ecosystem services) and the timing (when rapid responses may occur) of local sensitivities to multiple interacting stressor and perturbations.

An ecosystem stewardship framework is one strategy to address this challenge and to best manage for vulnerability, foster resilience, and guide positive transformations. To achieve socially beneficial outcomes and reduce the risk of bad outcomes, the framework must go beyond the traditional vulnerability perturbation– stressor– consequence mindset. For instance, it is critical to take into account that systems, as well as particular components within a system, are rarely equally vulnerable or equally resilient. Stochastic and nonlinear elements operating on and within a coupled system can give rise to unexpected or surprise outcomes (Holling and Gunderson 2002; Folke 2006; Peters et al. 2004). Determining cause and effect links that affect vulnerability at the local and regional scales will be essential to developing assessment frameworks and institutional structures that pragmatically link vulnerability analyses to decision making (Chapin et al. 2011). This approach will need to be explicitly focused on human norms, values, and well-being and m\ust therefore continually be debated and reassessed by stakeholders.

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4.02 Impacts of Land-Use Change to Ecosystem Services

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Glossary

Ecosystem services Goods with direct market values, and services that maintain the production of goods and biodiversity (sensu 1997).

Eutrophication The enrichment of surface waters with plant nutrients (http://www.org/docrep/w2598e/w2598e06.htmfao).

Globalization The process by which businesses or other organizations develop international influence or start operating on an international scale (*Oxford Dictionary*).

Human footprint (or Ecological footprint) The area of productive land and water ecosystems required to produce the resources that the population consumes and assimilate the waste that the population produces (after Wackernagel and Rees 1996).

Invasive species A species or taxon that is non-native (or alien) to the ecosystem under consideration, and whose introduction causes or is likely to cause economic or environmental harm or harm to human health (Clinton 1999; Executive Order 13112).

Urbanization Land-use conversion from agriculture or from forests, deserts, or other natural habitats for the development of homes, roads, and other facilities related to human habitation.

4.02.1 Introduction

Ecosystem services may be broadly defined as goods with direct market values, and services that maintain the production of goods and biodiversity (Daily 1997). When we think of ecosystem services, we often think of food, energy, clean water and air, and natural or semi-natural habitats that provide us with recreational opportunities, non-game wildlife habitat, and esthetic values. Charles and Dukes (2007) further define ecosystem services as:

1. Provisioning services such as food, freshwater, fiber, fuel, genetic resources, medicines, and ornamental resources;
2. Regulating services obtained by regulating ecosystem processes such as air quality regulation, flood control, water treatment, disease and pest control, pollination, erosion control, and coastal storm protection;
3. Cultural services, or non-material benefits, such as esthetic values, recreation–tourism, spiritual values, educational–scientific values, cultural heritage values, inspiration, and sense of place;
4. Supporting services that are necessary for the maintenance of the other services such as photosynthesis, primary production, nutrient cycling, water cycling, soil formation and maintenance of fertility, and atmospheric composition.

As humans have evolved and increased in numbers, they have come to directly and indirectly affect the quantity, quality, and delivery of ecosystem services from the world around them. Modern humans have roamed the planet for tens of thousands of years, but most human-caused land-use change has occurred in the past 1000 years. A recent synthesis by Goldewijk et al. (2011) reported that cropland occupied <1% of the global ice-free land area until AD 1000 (Table 1), with a similar area used as pasture lands. Croplands and pasture lands rose slowly until AD 1700, then they exponentially increased by AD 2000. Global croplands represented 11% of ice-free land in AD 2000 (15 million km^2), while pasture area increased to 24% of the ice-free land in AD 2000 (34 million km^2).

The rapid rate of land-use change is driven primarily by human population growth (Table 2). We need to eat (although our trophic position (carnivore versus herbivore) is important here).

Table 1 Global cropland and pasture area estimates for 10 000 BC to AD 2000

Year	*10 000 BC*	*5000 BC*	*AD 1*	*AD 500*	*AD 1000*	*AD 1500*	*AD 1600*	*AD 1700*	*AD 1800*	*AD 1900*	*AD 1950*	*AD 2000*
Cropland (10^6 km^2)	0.000	0.048	1.31	1.24	1.53	2.32	2.55	3.00	4.19	8.50	12.14	15.32
Pasture (10^6 km^2)	0.000	0.004	1.06	1.08	1.43	2.24	2.88	3.24	5.13	12.93	24.66	34.29
Population (10^6)	2	18	188	210	295	461	554	603	989	1654	2545	6145
ha per capita Cropland	0.00	0.24	0.52	0.43	0.36	0.33	0.29	0.30	0.24	0.35	0.33	0.16
ha per capita Pasture	0.00	0.02	0.56	0.51	0.48	0.49	0.52	0.54	0.52	0.78	0.97	0.55

Adapted from Goldewijk, K. K., A. Beusen, G. van Drecht, and M. de Vos, 2011: The HYDE 3.1 spatially explicit database of human-induced global land-use change over the past 12,000 years. *Global Ecol. Biogeogr.*, **20,** 73–86.

Table 2 Land-cover class area in 1992, area converted to urban land cover, and percent of change from 1992 to 2001

Class (NLCD1992-30 m)	*Area (ha)*	*Converted to urban (ha)*	*Percentage (%)*
Barren	9 257 699	10 716	0.115
Forest	213 527 204	905 543	0.424
Grass–shrub	284 195 691	416 603	0.147
Agriculture	182 456 109	803 736	0.441
Wetlands	37 392 477	89 750	0.240

From Stohlgren, T. J., C. S. Jarnevich, and C. P. Giri, 2010: Modeling the human invader in the United States. *J. Appl. Remote Sens.*, **4,**12, used with permission.

Consider for a moment the human population of 1.6 billion in AD 1900 rising to over 6.1 billion in 2000, and the recent news that the 7 billionth person on earth was born in 2011. In this chapter, we review the implications of land-use change on ecosystem services in the broadest of ways (i.e., any aspects of ecosystems utilized (actively or passively) to produce human well-being (Boyd and Banzhaf 2007; Fisher et al. 2009)).

It is clear that the landscape is being quickly transformed. For example, it is rather obvious that agricultural land increased at the expense of natural grassland habitat and to a lesser extent of forests (Goldewijk 2001). Shrinking availability of flat, fertile croplands (Figure 1) has led to an expanding human footprint into hills and mountains (DeFries et al. 2010; Figure 2). Future demand for food may result in increased terracing, and increased conversion of mountainous forests and woodlands into agricultural fields (Table 3; Lambin and Meyfroidt 2011). Further intensification of farming practices includes increases in mechanized equipment, long-distance irrigation, and heavy reliance on fertilizers and pesticides. Thus, while one component of ecosystem services (i.e., food) gets delivered, a suite of other ecosystem services (e.g., clean air and water, plant and wildlife habitat, recreational services) may be simultaneously degraded.

Throughout this chapter, we show that the spread of humans, agriculture, and urbanization are the proximate causes of encroachment on natural areas, habitat degradation, contaminants as by-products, and the introduction of harmful invasive species around the globe.

Table 3 Estimates of land use in 2000 and additional land demand for 2030

Land use category	*Low (Mha)*	*High (Mha)*
Land use in 2000		
Cropland	1510	1611
Pastures	2500	3410
Natural forests	3143	3871
Planted forests	126	215
Urban built-up area	66	351
Unused, productive land	356	445
Projected land use for 2030		
Additional cropland	81	147
Additional biofuel crops	44	118
Additional grazing land	0	151
Urban expansion	48	100
Expansion industrial forestry	56	109
Expansion of protected areas	26	80
Land lost to land degradation	30	87
Total land demand for 2030	285	792
Balance (unused land in 2000 – land demand in 2030)		
With no deforestation	+71	−347
Clearing of natural forests	152	303
With deforestation	+223	−44

*These values were derived from the literature and selected based on an expert judgment, evaluating the realism of underlying assumptions, looking for a convergence of evidence, and using 2000–2010 observations as a reality check (references and explanations in SI Text). The low estimates represent a conservative view of both land reserve and additional land demand, whereas the high estimates represent a slightly bolder view. From Lambin and Meyfroid (2011).

Consider the rapid loss of forest cover. Forests filter our air, protect soils from erosion, and provide habitat for wildlife and pollinators. A recent study by Hansen et al. (2010) quantified gross forest cover loss from 2000 to 2005 on our planet. They found that 1 011 000 km^2 representing 3.1% of total global forest cover was lost during the 5-year period. Boreal forests suffered the largest losses, followed by humid tropical, dry tropical, and temperate forests. Brazil lost over 165 000 km^2 of forests followed by Canada at 160 000 km^2. While the remote sensing efforts could not accurately estimate recovery rates, the numbers represent alarming rates of land-use change.

Figure 1 Mount Raung from Kalibaru, photo by Jean-Marie Hullot number 388 (public domain; http://www.fotopedia.com/items/jmhullot-POptPjropKg).

Figure 2 Ready to harvest – Shengcun Rice Terracesphoto by avlxyz (public domain; http://images.cdn.fotopedia.com/flickr-2342348329-original.jpg).

In the next section, we discuss the human footprint in more detail. The prevailing themes of this chapter are to aid in the transition to sustainability of resources (Matson 2009), and to improve understanding of the potentially adverse effects of land-use change on the delivery of all ecosystem services.

4.02.2 The Increasing Urban Footprint

As the human population grows, the human footprint expands. On the surface of the world, cities cover <1% of the land, but they concentrate >50% of the population and 70–90% of economic activities (Schneider et al. 2009, 2010). This, in turn, concentrates energy use and natural resource consumption; land, water, and air pollution; and the percent of impervious surface in urban areas, which all affect ecosystem goods and services. Humans are going urban. This has not always been the case. It was not until 2008 that the global urban population exceeded the non-rural population, according to Seto and Shepherd (2009). These authors also estimate 'that by 2050, 70% of the world population will live in urban areas, with more than half of them concentrated in Asia.' Since urban land-use and land-cover changes may have considerable impacts on climate, climate records may increasingly show an 'urban heat island effect,' which is more significant during the night than day, and show greater differences in urban and rural gradients (Seto and Shepherd 2009).

However, human activities associated with trade and transportation of goods to and from urban centers create an ever-expanding web of economic activity over much broader areas. For example, Stohlgren et al. (2010) quantified changes in 'urban' 30-m cells from LANDSAT from 1992 to 2001 (**Figure 3**). They found that urban areas represented 5.1% of the lower 48 United States in 2001, but that urbanization increased 7.5% (18 112 km^2) in the 9-year period – an area the size of Massachusetts.

Interestingly, the spread of humans was easily predicted with over 92% accuracy, based on the growing degree days, elevation, humidity, and slope. Low-elevation, warm-humid areas with slopes <10% were particularly prone to conversion to urban land use. Half of the land conversions came from forests and half from agricultural lands, but both reduce, at least temporarily, ecosystem services (**Table 2**).

Forest and agricultural lands contribute most to the urban landscape, but wetlands contribute twice that of barren lands (**Table 2**). Why is this important? Direct habitat loss, especially loss of wetlands, continues to be seen as the primary cause for species decline (Stuart et al. 2004). Undisturbed wetlands provide more oxygen for us to breathe, filter more water for us to drink, and produce more wildlife for us to enjoy compared to disturbed wetlands (Tu 2009). Urbanization begets landscaping. Landscaping services have flourished generating almost $60 billion in annual sales in 2007 (Census-Bureau 2007; http://www.census.gov/econ/). Many alien species are used in landscaping, and human-dominated landscapes generally require more water, fertilizers, and pesticides to maintain. Questions remain about the direct effects of urbanization on species persistence, conservation of

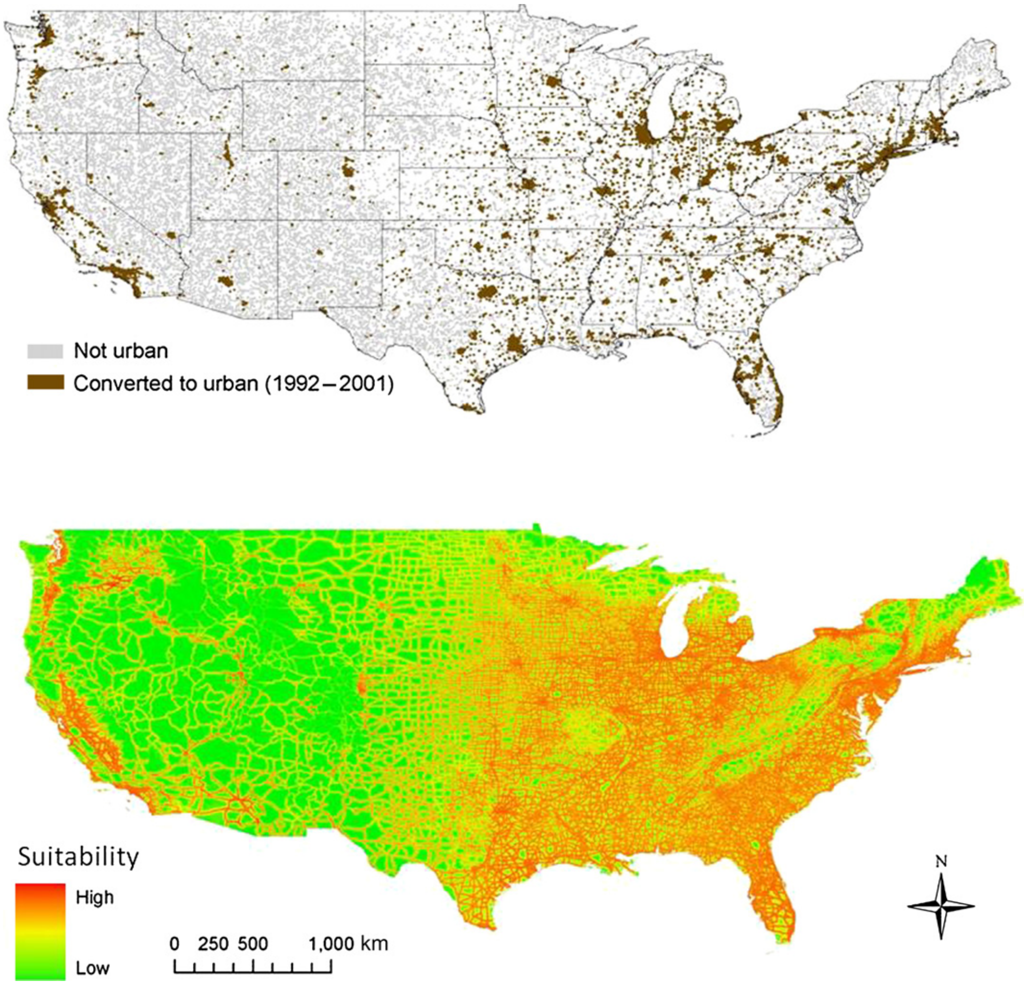

Figure 3 Rate of land-use conversion between 1999 and 2008 in the conterminous United States. Adapted from Stohlgren, T. J., C. S. Jarnevich, and C. P. Giri, 2010: Modeling the human invader in the United States. *J. Appl. Remote Sens.*, **4,** 12.

biodiversity, and climate system, but the examples described later in the chapter provide insights on the direction and magnitude of change.

4.02.3 Invasive Species and Ecosystem Services

Trade and transportation have increased over 40-fold in 100 years, reshuffling the species around the globe as geographic isolation becomes a thing of the past (Mack 2001). Alien species are now common components of floras worldwide (Stohlgren et al. 2011). Human-assisted migrations and the unintentional transportation of species will further spread alien species from local to global scales (**Figure 4**). For example, modeling the current distribution of African Fountain Grass (*Pennisetum setaceum*) helps to assess the invasive species (**Figure 4**, top) and how the habitat suitability of the species may be altered by future climate (**Figure 4**, middle). However, understanding the potential spread of the species is ludicrous without understanding, measuring, and predicting the sales and distribution of the species from commercial nurseries around the United States (**Figure 4**, bottom). Many invasive species are commercially sold and transported.

Charles and Dukes (2007) attempted to summarize the potential impacts of invasive species on ecosystem services. Unfortunately, they reported that researchers and policymakers rarely directly addressed the connection between invasions and ecosystem services. Assessments of the economic impacts of invasive species (e.g., Pimentel et al. 2005) cover control costs without directly addressing ecosystem services. Likewise, drastic changes to biodiversity are seen locally, such as the loss of bird species on Guam due to the Brown tree snake (Rodda et al. 1997), but continental-scale and global scale reports tend to be qualitative (e.g., Wilcove et al. 1998). Thus, it has been difficult to quantify the effects of invasive species on market and non-market ecosystem services.

A recent study from Europe provides an excellent model of how this problem may be addressed. Vila et al. (2010) conducted a comprehensive assessment of the impacts of alien plants, vertebrates, and invertebrates – in terrestrial, freshwater, and marine environments – on ecosystem services. They found 1094 alien species with documented ecological impacts, and 1347 alien species with economic impacts. Terrestrial invertebrates and terrestrial plants caused the greatest impacts. The North Sea was the maritime region with the greatest impacts from aquatic species. The authors also reported that across taxa and regions, ecological and economic impacts were highly correlated. Terrestrial vertebrates are responsible for the greatest range of impacts across Europe.

However, because some alien invasive species may have both positive and negative effects, there are trade-offs to consider. For example, Patel (2011) reported that *Parthenium hysterophorus*, a noxious weed from Mexico, now found in America, Asia, Africa, and Australia, can cause allergic respiratory problems, dermatitis, and genetic mutations in humans and livestock. Crop production can be greatly decreased by the competitive growth of *P. hysterophorus*, or due to its allelopathic chemicals. It also threatens biodiversity. However, *P. hysterophorus* may have health benefits for some people. It may be 'a remedy for skin inflammation, rheumatic pain, diarrhea, urinary tract infections, dysentery, malaria, and neuralgia,' according to Patel (2011), so the plant's positive aspects must be evaluated along with its negative aspects.

Bees provide another example of trade-offs to consider. Alien bee species aid in pollination, but the Africanized honey bee is a danger to human health. Many alien fish species provide recreational opportunities, but they may transmit whirling disease to native fishes. Alien zebra mussels may filter water, but they may also clog pipes cooling nuclear power plants. Alien shrubs, such as tamarisk, may provide some local habitat for threatened and endangered species, such as the southwest willow flycatcher (York et al. 2011). However, the invasive tamarisk may cause other problems such as increased fire risk, soil salinization, and pre-emptive water use in arid systems (Zavaleta 2000). Charles and Dukes (2007) conclude:

> Virtually all ecosystem services can be negatively impacted by invasive species, although positive impacts do exist. Many invasive species cause cascading effects in communities and/or affect both biotic and abiotic components of ecosystems. This usually leads to an influence on multiple ecosystem services.

4.02.4 Additional Effects of Land-Use Change

Direct effects of land conversions include direct loss of habitat generally causing many potentially negative effects to ecosystem services. However, there are indirect effects too. In this section, we discuss declines in habitat quality, potential effects of habitat fragmentation, altered disturbance regimes, livestock grazing, road building, and water storage and diversions needed to support our growing population.

4.02.4.1 Declines in the Quality of Natural Habitats and Habitat Fragmentation Effects

Declines in habitat quality can occur when forests are converted from old growth forests to second growth forests, especially for old-growth-dependent species such as the marbled murrelet (*Brachyramphus marmoratus*), northern spotted owl (*Strix occidentalis caurina*), and red-cockaded woodpecker (*Picoides borealis*), which are often prized by conservationists. There is conventional wisdom that small, isolated wildlife populations are more susceptible to extirpation and extinction (Gilpin and Soulé 1986), so the impacts of land-use change on habitat loss, habitat fragmentation, and loss of connectivity of sensitive habitats may combine to increase extinction rates of species of concern to society. The direct effects of land-use change are easily measured, such as the loss of over 50% of the wetlands in the United States since AD 1600 (http://water.epa.gov/type/wetlands/vital_status.cfm). Declines in habitat quality are more difficult to measure. However, land use has clearly affected habitat quality for numerous species and particularly many old-growth dependent species (Kerley et al. 2011 for a review).

The effects of habitat fragmentation have been poorly measured to date. Fahrig (2003) reported that empirical studies suggest that habitat loss has large, consistently

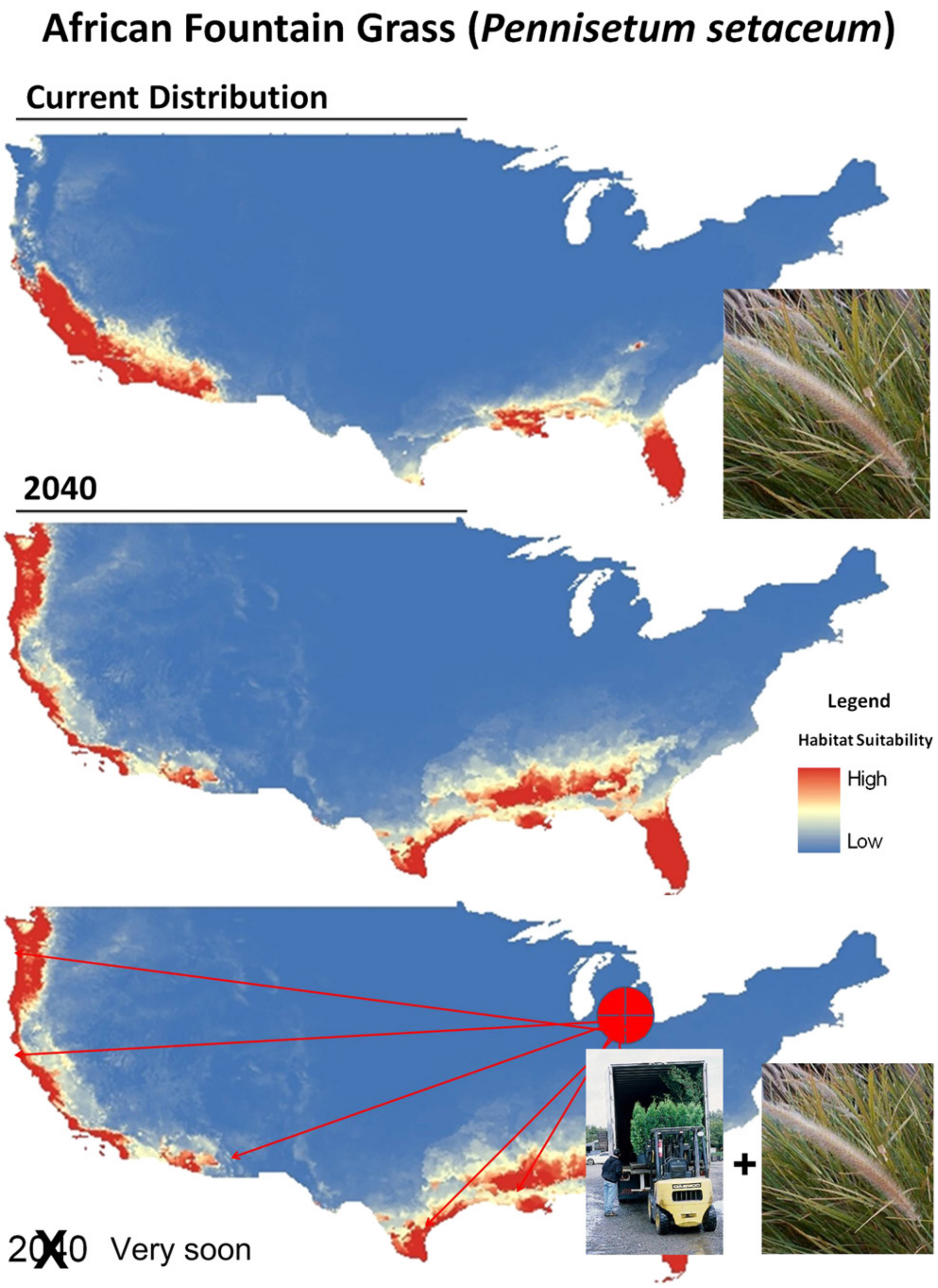

Figure 4 Modeling the current distribution of an invasive species African Fountain Grass (*Pennisetum setaceum*) (top), a potential future distribution of the species given a future climate change scenario (middle), and the hypothetical spread of the species because it is sold in commercial nurseries around the United States (bottom).

negative effects on biodiversity, but that habitat fragmentation per se has much weaker effects on biodiversity, and such effects may be positive or negative. Additional research might be better focused on the more direct effects of habitat loss (Hodgson et al. 2011).

4.02.4.2 Widespread Grazing of Domestic Livestock

Grazing lands in the Unites States cover more than 350 million ha, generate $40 billion in income, and maintain over 100 million livestock (Krueger et al. 2002), but there have been no complete, quantitative assessments of the cumulative effects of grazing on ecosystem services. It is a complicated issue because of the many positive and potentially negative economic and environmental effects, strong social pressures, and politically sensitive underpinnings. The qualitative overview by Krueger et al. (2002) discusses positive aspects of grazing related to maintaining rural economies, reducing wildfire fuels, and managing ‘desirable’ vegetation communities. The review also discusses environmental impacts on soil, water quality, riparian areas, and biodiversity, including invasive plant species. Several site-specific studies cited in the report show that livestock affect soils via compaction, erosion, and changes in the plant community; and water quality via manure and urine inputs. However, we found no comprehensive qualitative assessments of livestock grazing, despite the obvious need.

4.02.4.3 Road Building

Roads and roadsides cover less than 1% of the United States, but the 6.2-million-kilometer system connects every city and town and infiltrates every county (Forman and Alexander 1998). Negative ecological impacts associated with roads include erosion, altered hydrological systems, microclimates, and conduits for harmful invasive plants, animals, and diseases. The effects of roads can be measured from meters to kilometers away from the physical feature. As described by Forman and Alexander (1998), roads can have a great effect on wildlife. Road kill is a common source of wildlife mortality. Meanwhile, road avoidance by wildlife can also alter migration patterns and the genetics of populations. That 1% direct loss in natural vegetation habitat by road building may actually affect 15–20% of the land in the United States.

Roads are major corridors of invasion. For example, Gelbard and Belnap (2003) found that roads were a large contributor to the spread of alien grasses and forbs in the semiarid grasslands, shrublands, and woodland communities of southern Utah, United States. The cover of *Bromus tectorum* (cheatgrass) was three times as great along roads compared to non-road interior areas. Other alien plants, animals, and diseases are likely facilitated by transportation networks. As with the issue of grazing, a comprehensive, quantitative assessment on the effects of roads is badly needed.

4.02.4.4 Water Control – Dams, Diversions, and Irrigation

The scope of this land-use effect is difficult to fathom (pun intended). It is estimated that 77% of the total discharge of the 139 largest river systems in the northern third of the world is affected by dams, diversions, and irrigation (Dynesius and Nilsson 1994). Many rivers now fail to reach the sea in many years, including the Nile River in Africa, and the Colorado River in the United States, largely to meet food production demands (Postel 1998). Dams provide energy, and reservoirs provide water, but there are mounting ecological impacts from human-altered hydrology. Reservoirs have become refuges for sediments, chemical waste, and invasive alien fishes and plants. According to Postel (1998, p. 636), "Large dams and river diversions have proven to be primary destroyers of aquatic habitat, contributing substantially to the destruction of fisheries, the extinction of species, and the overall loss of the ecosystem services on which the human economy depends. Their social and economic costs have also risen markedly over the past two decades." However, much more quantitative work is needed to fully assess the cumulative positive and negative effects of dams, diversions, and irrigation on ecosystem services (see http://www.nationalrivers.org/node/490inter).

4.02.4.5 Wildfire, Fire Suppression, and Managed Fires

Many natural disturbances such as volcanic eruptions, hurricanes, tornados, floods, insect outbreaks, and wildfires affect ecosystem services. We report on wildfire, fire suppression, and managed fire in the United States as an example of the effects of the disturbance of ecosystem services because (1) humans have had a large effect on the location and size of fires as either the source of ignition or in suppression efforts and (2) the direct and indirect effects of fire can be substantial on local and regional air quality, water quality, carbon storage, wildlife habitat, esthetics, and human health.

Fires in the 1900s in the United States were sporadic and patchily distributed. There were extensive wildfires in the 1930s. The decline in land area burned since the late 1950s has been attributed to wildfire awareness campaigns (e.g., Smokey Bear) and the advent of effective ground-based and aerial fire suppression coordination. According to the National Interagency Fire Center website, between 1983 and 2010, almost 50 million hectares burned, with an average of almost 1.8 million hectares burned per year (http://www.nifc.gov/fireInfo/fireInfo_stats_totalFires.html). Despite costs to property and human health, natural fire is important to the regeneration of many forest types in the United States, and is a valuable process in maintaining ecosystem function (Arno 2000). However, fire suppression may be affecting a greater land base than wildfire.

Fire suppression is a dual-edged sword. While it protects the current crop of vegetation, which stabilizes soils, filters air, and provides for wildlife habitat and recreational, continued fire suppression results in buildup of fuels and sets the stage for potentially catastrophic fires later. Managed fire produces smoke, resulting in air quality issues, but it may save lives and property, albeit with some risk, especially at the urban–wild land interface. Much like terracing in agriculture, urban development is spreading further into fire-prone areas (e.g., chaparral in California, pine woodlands in Colorado). Fire ecologists are just now beginning to take a comprehensive look at the effects of fire suppression on natural systems and the urban–wild land interface (Davis et al. 2010).

In addition to human encroachment into fire-prone areas, fire management tools such as forest thinning, clearing around structures, and use of prescribed burning all carry risks for human safety. Post-fire activities such as seeding with alien grasses, or the natural spread of alien grasses, may increase the frequency and intensity of wildfire in fire-prone communities (Hunter et al. 2006). Humans demanding privacy, natural settings, and fire protection may not get them all.

4.02.4.6 Use of Fertilizers, Pesticides, and Herbicides

Land-use changes into agriculture or urban landscaping generally cause an increase in the use of fertilizers, pesticides, and herbicides. Tilman (2001) estimates that during the next 50 years of rapid agricultural expansion, demand for food will be a major driver of global environmental change with 10^9 ha of natural ecosystems to be converted to agriculture by 2050. This, in turn, may cause 2.4- to 2.7-fold increases in nitrogen and phosphorus application and further eutrophication of terrestrial, freshwater, and near-shore marine ecosystems. He predicts similar increases in pesticide use.

Increased use of water (and energy) to support agriculture and urban landscapes provides the mechanism for the eutrophication of streams and rivers. 'Eutrophication' is the enrichment of surface waters with plant nutrients (http://www.fao.org/docrep/w2598e/w2598e06.htm). Agriculture is often seen as a major contributor to the eutrophication of surface waters. An obvious trade-off exists between the need to feed an ever-growing human population and the need to maintain water quality and the many other ecosystem services derived from streams and rivers with high environmental integrity (Matson Robertson and Swinton 2005).

4.02.4.7 Other Indirect Effects of Land Use

There are many by-products of land-use change. Beyond the human footprint is an ever extending zone of influence. Pets escaping, such as dogs and cats affecting local bird populations (Leu et al. 2008), but escapes of more insidious pets such as Burmese pythons in Florida, or aquatic weeds and disease carrying snails from aquaria are other examples of indirect urbanization effects. Factory and energy plant smokestacks and car exhaust pipes send air pollution around the globe. We facilitate dust storms that bridge continents with land-use decisions. Abandoned mines continue to leak heavy metals into domestic water supplies. New types of energy development, such as fracking for oil and gas, are already creeping beneath urban and suburban homes. We see sewage treatment plants and landfills at the edge of town, but rarely view our refuse dumped in the bottom of the ocean. We store nuclear waste below ground, and space junk orbits in the skies above. The ecosystem service furthest from our minds is disposal.

4.02.5 Challenges and Solutions

Lambin and Meyfroidt (2011) found that economic globalization accelerates land conversion. This creates a challenge in delivering ecosystem services, while reducing the harmful effects of deforestation, contaminants associated with agriculture and urbanization, and the accelerated exchange of harmful alien species – plants, animals, and diseases. Local solutions may include carefully adapting agricultural intensification to reduce the use of fertilizers, pesticides, and water (Ahrens et al. 2010). Regional to national solutions include land-use zoning, forest protection, an increased reliance on imported food and wood products, the creation of off-farm jobs, and foreign capital investments (Lambin and Meyfroidt 2011). Increasing land use will not be easy in many cases, since social aspects and local economic forces may slow progress (Matson 2009).

A key endeavor for conservation may be to focus on minimizing direct habitat loss, especially the direct losses of the habitats for rare, endangered, or threatened species. Attention to the proximate causes of change: overpopulation, demand for resources, unsustainable agriculture and forestry practices may provide a good place to start. The connections are clear and unambiguous. Human population increase will lead to additional agriculture, a decrease in biodiversity, and an increase in the use of pesticides and herbicides that will affect all ecosystems surrounding the agricultural land (Tilman et al. 2001).

Managing the increasing human footprint is important. We need to more accurately quantify the cumulative effects of agriculture, deforestation, road building, and urbanization (Leu et al. 2008). Prime consideration for conservation areas may be based on the rarity of habitat, unique species assemblages in those habitats, and potential for persistence of

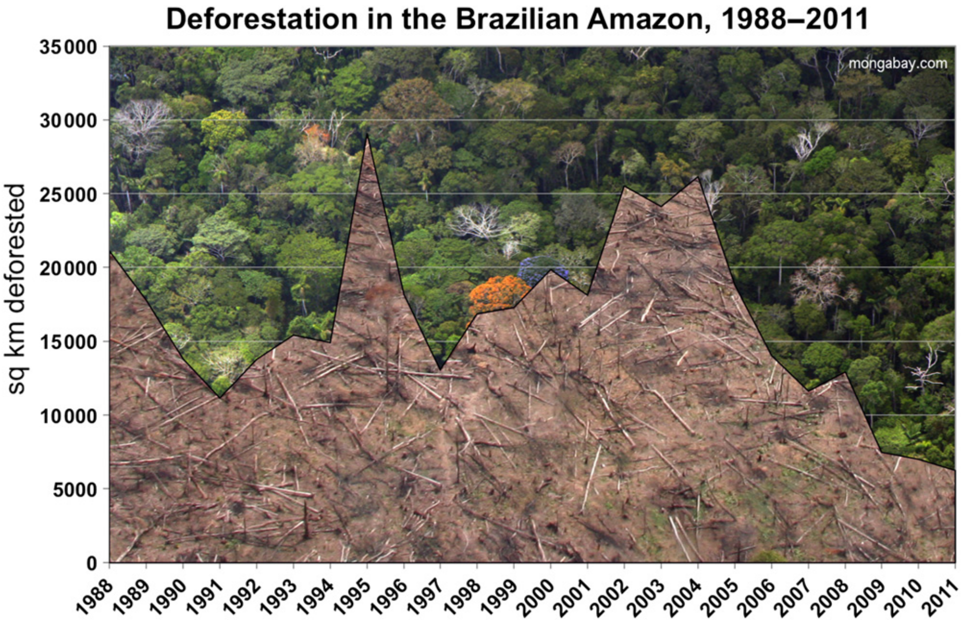

Figure 5 Deforestation in the Brazilian Amazon. http://www.mongabay.com/brazil.html.

ecosystem services from those rare types under different management scenarios.

Sustainable development will include trade-offs. Unconstrained human population growth may result in difficult choices – whether to build atop prime agricultural lands or further into natural, semi-natural, or fire-prone habitats. The water and energy needs of a growing or spreading population must prepare for occasional long-term droughts. Long-range conservation planning is essential. We need accurate forecasts and scenarios to guide sustainable land use (Turner et al. 2007; Wirsenius et al. 2010).

Trade and transportation have increased 40-fold in our lifetime (Stohlgren et al. 2011). Many harmful plants, animals, and diseases will accompany future changes in land use and climate. Balancing trade-offs and a triage of research needs will be necessary. Regional and local changes in climate statistics may play a role, but it will be slower and more long term, and less so a proximate driver of change to ecosystem services relative to direct habitat loss and invasive species.

Economics drives land-use change. Deforestation in Brazil (**Figure 5**) is driven by industrial agriculture and land speculation, with more than 70% of deforested land ending up as cattle pasture. It is these high commodity prices that create incentives for deforestation.

In the end, it may come down to engineering better solutions to sustain life and ecosystem services (e.g., Matlock and Morgan 2011). More people will create a greater demand for resources. Increased demand for resources will affect habitat quantity and quality, unless we manage land use wisely. Difficult decisions will require the best data and predictive models available. We have to ask ourselves, ‘How much are we leaving for future generations to ensure quality ecosystem services in the future?’ In the words of Chief Seattle:

> Humankind has not woven the web of life. We are but one thread within it. Whatever we do to the web, we do to ourselves. All things are bound together. All things connect.

See also: Invasive Plants and Animal Species: Threats to Ecosystem Services; Connecting Nitrogen Deposition and Ecosystem Services; Does Climate Change Increase the Risk of Disease? Analyzing Published Literature to Detect Climate–Disease Interactions; Vulnerability of Pollination Ecosystem Services; Effects of Carbon Dioxide Enrichment on Plants.

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4.03 Connecting Nitrogen Deposition and Ecosystem Services

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Glossary

Critical loads The input of a pollutant below which no known detrimental ecological effects occur over the long term.

Ecosystem services Outputs of ecological functions or processes that directly or indirectly relate to human well-being.

Reactive nitrogen Includes all forms of biologically, chemically, and radiatively active nitrogen compounds in the atmosphere and biosphere.

4.03.1 Introduction

Nitrogen (N) is an essential element required for life, but availability of N often limits primary production in terrestrial and aquatic ecosystems (Elser et al. 2007; LeBauer and Treseder 2008). Human population growth and increased demands for energy, transportation, and food, combined with technological advances, have lead to increased N fixation (Townsend et al. 2003; Galloway et al. 2008). A substantial fraction of the reactive N used for human needs is eventually transferred to the environment. Nitrogen cycling is accelerated by human activities through the application of fertilizers, the cultivation of N_2-fixing crops such as soybeans, the combustion in power plants and vehicles, and through disposal and treatment of human and animal wastes.

N release to the environment during the last century has more than doubled globally, fundamentally altering ecosystem structure and function in many places (Vitousek et al. 1997; Davidson et al. 2012). Nitrogen deposition continues to reduce biodiversity of native ecosystems and increase the dominance of invasive species (Bobbink et al. 2010). Nearly two million Americans live in homes where the well water contains nitrate concentration at or above the drinking water standard for human health (Compton et al. 2011). Currently, many streams in the United States are in poor condition due to excess nitrogen (Paulsen et al. 2008). Many lakes and terrestrial ecosystems exceed critical loads, defined as the input of a pollutant below which no known detrimental ecological effects occur over the long term (Baron et al. 2011; Pardo et al. 2011). Increases in reactive N mobilization have increased the production of N_2O, a greenhouse gas, and also now the dominant chemical that destroys the protective ozone layer (Davidson 2009; Ravishankara et al. 2009). Nitrogen loading alters the production of CH_4 and CO_2 in complex ways and contributes to particulate-driven cooling, and, as such, has the potential to warm and cool the climate (Davidson et al. 2012). Anthropogenic increases in N deposition have now been observed in even extremely remote high arctic lakes (Holtgrieve et al. 2011). Reactive N continues to have broad impacts on ecosystems and human health despite improvements in the scientific understanding of N loading and effects on the environment (Sutton et al. 2011; Davidson et al. 2012).

These fundamental changes to ecosystem structure and function in turn have altered key ecosystem services such as the provision of clean air and water, recreation, fisheries, forest products, esthetics, and biodiversity (Table 1). The Millennium Ecosystem Assessment (MA 2005) underscored that understanding the trade-offs inherent in controlling this class of environmental pollutant is one of the major challenges to be faced in the twenty-first century. The damages caused by this unintentional release of N from industry, agriculture, and transportation to the environment are considered externalities and are not included in the costs of nitrogen use (Kusiima and

Table 1 Ecosystem services and human benefits affected by increasing N deposition

Ecosystem service	*Direction of impact*	*Mechanism of impact on human benefit*
Production of food and materials	+	Increased production and nutritional quality of food, wood, and fiber crops during the last century
	+	Increased production of building materials and fiber for clothing or paper
	–	Stimulate ozone formation, which in turn can reduce agricultural and wood production
	–	Soil acidification, nutrient imbalances and altered species composition, and diversity in natural ecosystems, ultimately impacting stability and resistance to disease, weather extremes, invasive species, and fire
Fuel production	+	Increased use of fossil fuels to improve human health and well-being across the globe
	+/–	Increased N inputs required for some biofuel crops can affect other services
Clean air	–	Increased particulates (from NO_x and NH_x), which exacerbate respiratory and cardiac conditions
	–	Increases in ozone (NO_x-driven), which exacerbate respiratory and cardiac conditions
	–	Increased allergenic pollen production
Drinking water	–	Increased nitrate concentrations lead to blue baby syndrome, thyroid issues, and certain cancers
	–	Increased acidification and mobility of heavy metals and aluminum
Swimming	–	Stimulated harmful algal blooms that release neurotoxins (interaction with P)
	–	Increased vector-borne diseases such as West Nile, malaria, and cholera
Fishing	+	Increased fish production and catch for some very N-limited coastal waters
	–	Increased hypoxia and harmful algal blooms in coastal zones, closing fish, and shellfish harvests
	–	Reduced number and species of recreational fisheries from acidification and eutrophication
Hiking	–	Altered biodiversity, health, and stability of natural ecosystems
Climate regulation	+/–	Variable and system-dependent impacts on net CO_2 exchange
	–	Stimulate N_2O production, which is a powerful GHG
UV regulation	–	Increased N_2O release, which has strong ozone-depleting potential
Visibility	–	Increased NO_x in air stimulates formation of particulates, smog, and regional haze
Cultural and spiritual values	–	Altered biodiversity, food webs, habitat, and species composition of natural ecosystems
	–	Damage to buildings and structures from acids
	+/–	Harmful effects of N in countries distant from emission sources and some of the benefits, due to long-distance transport of N and globalization of industries and agriculture

Modified from Compton, J. E., J. A. Harrison, R. L. Dennis, T. L. Greaver, B. H. Hill, S. J. Jordan, H. Walker, and H. V. Campbell, 2011: Ecosystem services altered by human changes in the nitrogen cycle: a new perspective for US decision making. *Ecol. Lett.*, **14,** 804–815.

Powers 2010). An approach that explicitly examines ecosystem services and human well-being (Figure 1) could focus and augment more traditional approaches, which have had limited success and left us with continuing nutrient problems (US EPA 2009).

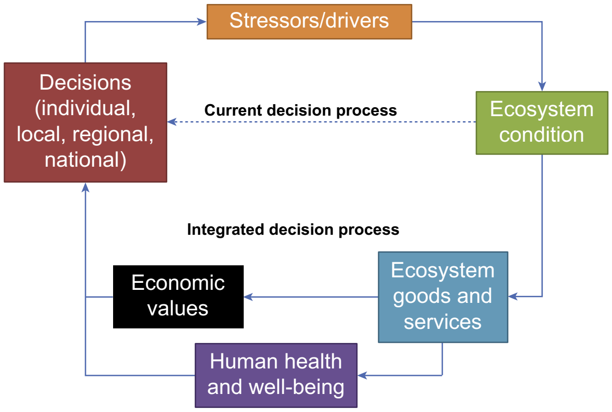
Stressors/drivers
Decisions (individual, local, regional, national)
Current decision process
Ecosystem condition
Integrated decision process
Economic values
Ecosystem goods and services
Human health and well-being

Figure 1 Current decision process generally incorporates response of ecosystem condition (e.g., concentrations, process rates, fluxes, species composition) to anthropogenic stressors and drivers, while an integrated decision process incorporates information about the impacts on ecosystem goods and services, human well-being, and economic values.

The goals of this chapter are to (1) review the state of the science connecting increasing N deposition to ecosystem services, (2) identify knowledge gaps in our understanding of the impacts of N deposition on ecosystem services, and (3) discuss the expectations and research needed to effectively connect ecosystem services science to policy into the future.

4.03.2 Defining an Ecosystem Services Approach

Ecosystem services are the aspects of nature that benefit people. Daily et al. (2009) define ecosystem services as the "conditions and processes through which natural ecosystems and species therein sustain and fulfill human life or have the potential to do so in the future." The Millennium Ecosystem Assessment (MA 2005) categorized services into provisioning, supporting, regulating, and cultural services. Others have refined this definition to improve the applicability of ecosystem services for decision-making, as outputs of ecological functions or processes that directly or indirectly relate to human well-being (Fisher et al. 2009). For the purposes of this chapter, an ecosystem services approach is defined as connecting human benefits to ecological structure and function, allowing for quantification of positive and negative impacts of decisions, being as complete as possible in quantifying the scope of impacts, and including an economic

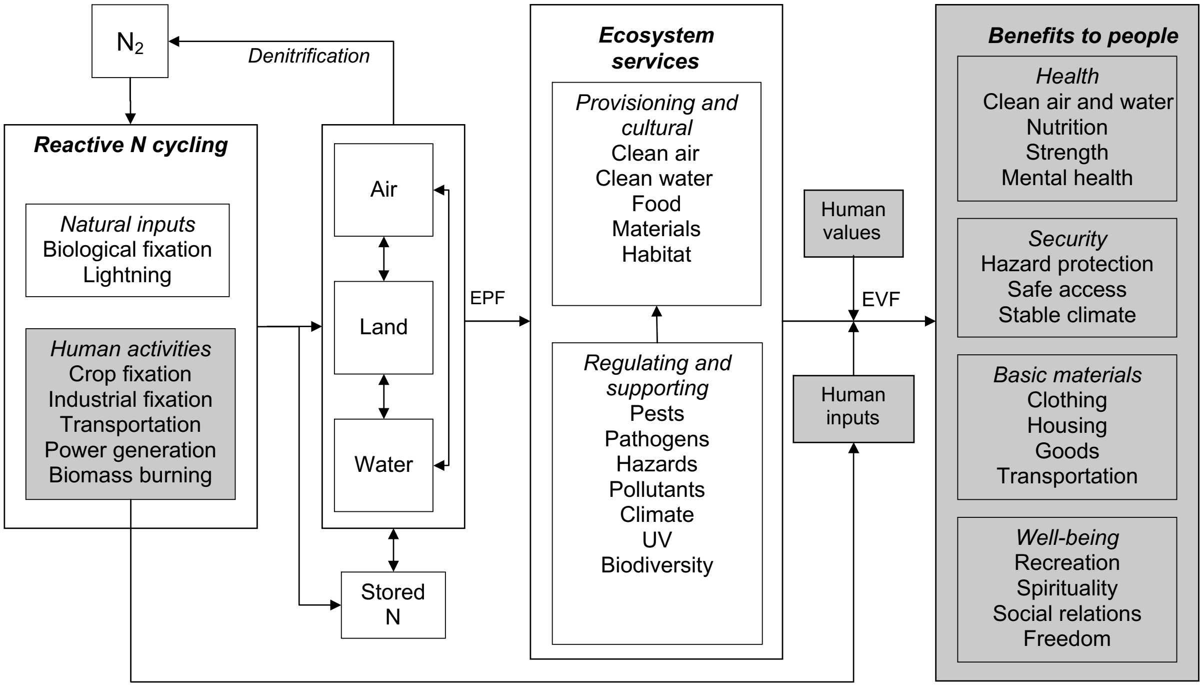
N₂
Denitrification
Reactive N cycling
Natural inputs
Biological fixation
Lightning
Human activities
Crop fixation
Industrial fixation
Transportation
Power generation
Biomass burning
Air
Land
Water
Stored N
EPF
Ecosystem services
Provisioning and cultural
Clean air
Clean water
Food
Materials
Habitat
Regulating and supporting
Pests
Pathogens
Hazards
Pollutants
Climate
UV
Biodiversity
Human values
EVF
Human inputs
Benefits to people
Health
Clean air and water
Nutrition
Strength
Mental health
Security
Hazard protection
Safe access
Stable climate
Basic materials
Clothing
Housing
Goods
Transportation
Well-being
Recreation
Spirituality
Social relations
Freedom

Figure 2 Connections among reactive nitrogen cycling, ecosystem services, and benefits to people. Clear boxes indicate ecological systems, gray shaded boxes represent human systems. EPF, ecological production function; EVF, ecological valuation function. From Compton, J. E., J. A. Harrison, R. L. Dennis, T. L. Greaver, B. H. Hill, S. J. Jordan, H. Walker, and H. V. Campbell, 2011: Ecosystem services altered by human changes in the nitrogen cycle: a new perspective for US decision making. *Ecol. Lett.*, **14,** 804–815.

valuation component. For example, prior to a decision related to a new regulation, such as a new air policy or a total maximum daily load (TMDL) for a stream reach, the costs and benefits of the decision are assessed. In general, the direct human health impacts have been well studied but the information on ecosystem impacts and connections to ecosystem services are often not suitably well understood to inform policy. This chapter attempts to make more of these connections and to identify gaps where we know there are effects but those effects are not well studied or connected to the driver, N load. We also discuss valuation of the costs or impacts where possible.

Figure 2 illustrates the links between N sources, N cycling, ecosystem services, and benefits to people. Many of the effects on structure and function alter the production of ecosystem services, such as the provision of food, water and materials, regulation of climate and UV protection, provision of clean air, and habitat and biodiversity for recreation and human well-being. Changes in ecosystem services alter the benefits for people, influencing air for breathing, visibility, esthetics, water for drinking, recreation, and a host of other services.

4.03.3 Connecting Effects on Ecosystem Structure and Function to Ecosystem Services

In the following section, we focus on several sets of key ecosystem services that directly link to management of N in the environment: (1) provision of clean air and water for direct human needs, (2) food, fuel, and fiber production, (3) maintenance of biodiversity and esthetics, and (4) climate regulation. This does not include all services potentially impacted by nitrogen deposition, but represents a number of key services. In some cases, much is known about the impacts on ecosystem structure and function, but the connection to ecosystem services and benefits to people may not yet be clear in the literature (see Figure 2). In those cases, this review attempts to connect the impacts on structure and function to services and benefits. In some cases, the impacts have been studied all the way through to economic valuation, and we are able to compare the relative impacts of nitrogen on these values with a simple metric of dollars per kg N ($/kg N). See Compton et al. (2011) for more detail on valuation of costs associated with reactive nitrogen. The EU Nitrogen Assessment (2011) also used this metric in their analysis on the costs and benefits of impacts.

4.03.3.1 Provision of Clean Air and Clean Water for Direct Human Needs

Tremendous benefits to human health and well-being have resulted directly or indirectly from human alteration of the N cycle, particularly in terms of nutrition, materials (e.g., wood, paper, fabric), and provision of heat, light, and transportation. Many of these positive impacts can be tracked through economic indicators. However, when N is transported downwind or downstream from sites where its use is primarily beneficial to humans, it can become a hazard to human health (Townsend et al. 2003). These detrimental impacts are more challenging to track and do not necessarily correlate with the benefits (Raudsepp-Hearne et al. 2010).

Air quality and consequent health effects strongly respond to changes in reactive N. NO_x is an important precursor of tropospheric ozone and particulate matter (with NH_x), which can increase rates of asthma and other respiratory issues, particularly in children and other vulnerable populations (Delucchi 2000). While many of these interactions occur in the atmosphere, the net resulting air quality is a result of interactions between atmosphere, biosphere, and hydrosphere, and, thus, the provision of clean air is considered to be an ecosystem service. On an annual basis, particulate exposure is estimated to cause nearly 130 000 premature deaths and ozone exposure another 7000 deaths, and there are thousands of hospital visits and other well-being issues related to respiratory issues triggered by reactive N (Davidson et al. 2012).

The provision of clean water for drinking and other domestic uses is a key ecosystem service, and unfortunately nitrate contamination in drinking water is a growing issue in the United States. The number of drinking water violations of the nitrate standard in community drinking water wells nearly doubled between 1998 and 2008 (US EPA 2009). Excess nitrate in drinking water has been associated with a number of illnesses, including blue baby syndrome and several types of cancers (Townsend et al. 2003; Ward et al. 2005). Although nitrate contamination of drinking water has an important and growing impact on this vital ecosystem service, atmospheric deposition does not generally lead to groundwater nitrate contamination. Instead, Agricultural fertilizer inputs are the dominant driver for groundwater contamination with nitrate, and atmospheric deposition is not a broadly important factor (Nolan et al. 2002).

Excess N in surface waters can have indirect effects on human health by stimulation of harmful algal blooms (HABs) that produce toxins (Camargo and Alonso 2006), outbreaks of dangerous pathogens, like *Cryptosporidium*, or simply unpleasant odors and tastes that are costly to remove. Even where nitrate concentrations are below the US EPA drinking water standard (10 mg nitrate-N l^{-1}), nitrate and eutrophication can increase treatment costs needed to create safe drinking water. Some treatment processes designed to remove the products of eutrophication can introduce harmful chlorination byproducts into drinking water (Cooke and Kennedy 2001). There is also some suggestion that N enrichment can exacerbate pathogens such as West Nile virus, pollen allergens, swimmer's itch, malaria, and cholera (Townsend et al. 2003; Johnson et al. 2010).

The costs of human health problems related to N have been evaluated in a number of studies and have generally been found to be the most costly impacts in a relative (per unit N) and absolute sense. In a detailed review of the valuation of air quality regulations on humans and ecosystems, mortality and illness associated with reactive N forms as precursors to PM and ozone were the most substantial of the measured effects (Chestnut and Mills 2005). A number of US and EU studies have also examined the cost of NO_x and NH_y effects on respiratory health; most recently the ExternE project determined the health impacts of reactive N in air to be $28 per kg NO_x-N and $16 per kg NH_3-N (Bickel and Friedrich 2005). Even in the Chesapeake Bay, where N deposition is not the largest source of N, the human health consequences of nitrogen forms in air had the highest quantifiable damage costs because of the high value placed on human health (Birch et al. 2011). Interactions of increased reactive N in the atmosphere through the multiple forms and by-products of nitrogen (ozone and particulates), biosphere, and hydrosphere clearly have profound impacts on human health and in turn well-being.

At certain levels of N loading, ecosystem services can actually mediate N impacts, particularly the provision of clean water for drinking. Plants, microbes, and soil organic matter can remove some of the added nitrogen along flow paths in soil, streams, and groundwater, serving as sinks for excess reactive N, providing an important ecosystem service that would cost several dollars per kg N in a sewage treatment plant. In particular, wetlands have significant capacity to remove N (Jordan et al. 2011). In some cases, large increases in reactive N can reduce the N storage capacity or uptake kinetics of these ecosystems (Perakis et al. 2005; Mulholland et al. 2008). One of the potential costs of reactive nitrogen is this reduction in the ecosystem services of water purification; however, we are not aware of an analysis that explicitly examines these costs.

4.03.3.2 Impacts on Food, Fuel, and Fiber Production

Because temperate ecosystems are often limited by the availability of reactive N, biological production can be increased by N additions in these systems. The broad benefits of N fertilization on food and material production are well known, particularly for agriculture, but the damages to these services caused by increasing N in the environment are not as well understood. Several studies have quantified damage costs of N on food and fiber production. One of the most complete national analyses of N deposition effects examined the consequences of US air pollution control policies (Chestnut and Mills 2005). Emissions of N and S oxides led to acidification and damage to materials that cost approximately $133 million annually prior to the US Acid Rain Program, 1990 Clean Air Act Amendments (Chestnut and Mills 2005). Nitrogen oxides also contribute to ozone formation in the troposphere, which can reduce crop and forest production in ways that could offset any fertilization effects, particularly in areas where N loading is already high. Ozone reductions projected to result from the 1990 Clean Air Act Amendments were estimated to provide a total annual benefit to the US commercial timber industry of about $800 million, and improved yields were estimated to benefit grain crop producers by $700 million in 2010 (Chestnut and Mills 2005). Increases in N also fuel UV damages to crop production and fisheries/corals, since N_2O is currently the most important contributor to the breakdown of stratospheric ozone (Ravishankara et al. 2009), although N deposition plays a small role in N_2O production.

There are some potential trade-offs between harmful and beneficial effects. While ozone and acidification may reduce productivity, increases in the availability of N (a limiting nutrient) may increase production of a particular species or groups of species. Thomas et al. (2010) clearly demonstrated that most tree species had faster growth rates as deposition increased over space in the northeastern United States, using an analysis of repeated sampling of forest inventory plots (**Figure 3**). The approximate enhancement in carbon gain was 40% above preindustrial N deposition at levels up to 11 kg N ha^{-1} yr^{-1}. While it is not clear what the net effect of these increases in productivity will be for timber production,

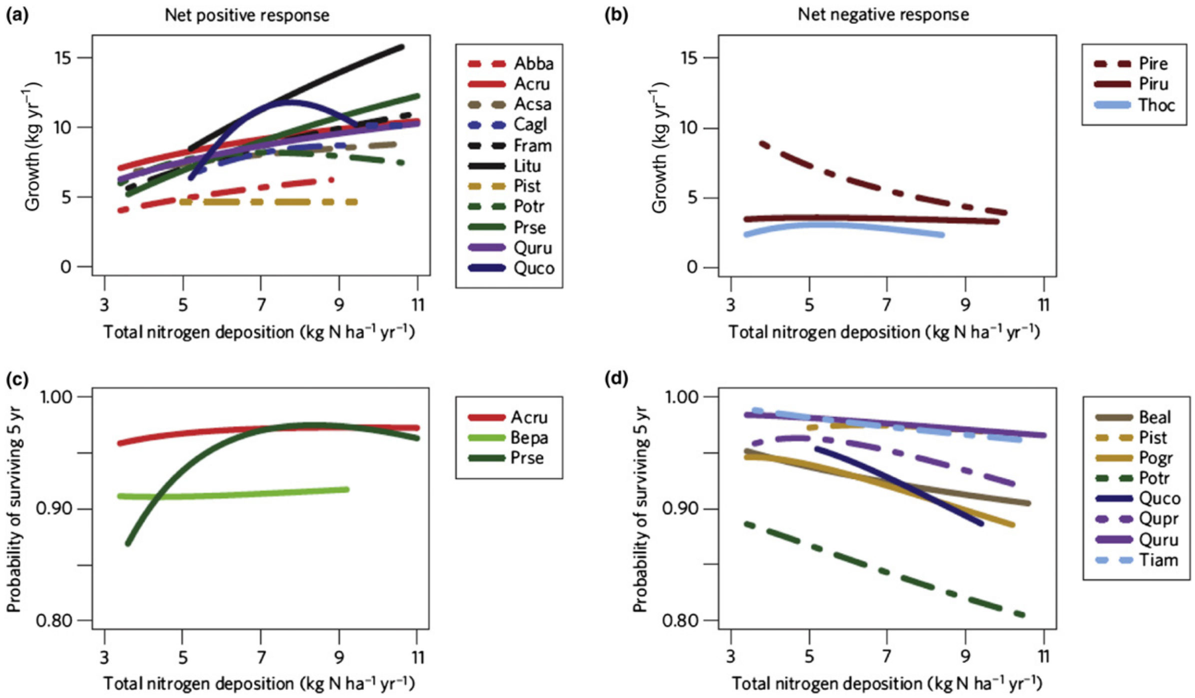

Figure 3 Growth and survival response to increasing N deposition. Annual above-ground carbon increment (a–b) and 5-year survival rate (c–d) as a function of total (wet C dry) inorganic N deposition for individual trees of the 24 most common species in a 19-state region of the eastern United States *(see original paper for species codes). Species that did not respond to nitrogen deposition are not shown.* Reproduced from Thomas, R. Q., C. D. Canham, K. C. Weathers, and C. L. Goodale, 2010: Increased tree carbon storage in response to nitrogen deposition in the US. *Nat. Geosci.*, **3,** 13–17.

the species with the largest positive growth responses were the valuable timber species tulip poplar and black cherry. By stimulating plant production, N inputs from atmospheric deposition may account for a significant fraction of current terrestrial C uptake in some systems (Liu and Greaver 2009). Productivity of grasslands and alpine ecosystems has also been shown to increase with N deposition, but is accompanied by a decrease in biodiversity (Bowman et al. 1995). We discuss this impact on biodiversity in a later section. Clearly an N-driven increase in terrestrial productivity could have important implications for timber production and other terrestrial products, but the net impacts and economic implications have not been broadly quantified.

In aquatic ecosystems, increasing N loads can also stimulate production, particularly in estuaries and near-coastal waters, but the relationship is not linear. At low N loading, fisheries may be limited by N, whereas increasing N loads can lead to eutrophication, hypoxia, and anoxia with the potential to reduce fish production (Breitburg et al. 2009). Acidification of sensitive surface waters can impact fish species composition (see biodiversity section below for more discussion). The desirability of enhanced production of any given species is somewhat variable: for example, greater algal production could ultimately lead to fish kills; atmospheric N loading could stimulate the production of undesirable or exotic species (e.g., Suding et al. 2004) leading to questions about how various increases in production should be valued. Despite the complexities, greater understanding of how to value the net benefits or detriments of N loading to the environment would significantly contribute to our understanding and ability to implement an ecosystem services approach to management of the environment and natural resources.

Harmful algal blooms and fish kills linked to N or other nutrients have caused substantial losses to the seafood industry. Whitehead et al. (2003) estimated that the lost consumer surplus due to a dinoflagellate (*Pfiesteria* sp.) related fish kill is between \$37 and \$72 million in the month following a fish kill. Production of shrimp and crabs in Gulf estuaries is large and sensitive to habitat loss (Jordan et al. 2009), and damage to this valuable fishery was one of the highest per kg N damages identified by Compton et al. (2011). However, more data on fisheries valuation impacts from reactive N are needed.

4.03.3.3 Maintenance of Biodiversity and Esthetics

Excess N has been repeatedly shown to reduce the biodiversity of natural ecosystems. A recent global analysis found that N deposition is the main driver of altered species composition in a range of ecosystem types (Bobbink et al. 2010). Species that tend to show increases in abundance are often non-native invasives with high vegetative and population growth rates, which have the potential to drive local populations of rare native species to extinction (Bobbink et al. 2010). Figure 4 shows the relationship between N deposition and declining biodiversity in European grasslands (Stevens et al. 2010).

The linkages between biodiversity and benefits to people are clear. Balvanera et al. (2006) review the impacts of biodiversity of ecosystem services, which include productivity, nutrient cycling, erosion control, and ecosystem stability (Figure 5). Ecosystem services associated with biodiversity can be

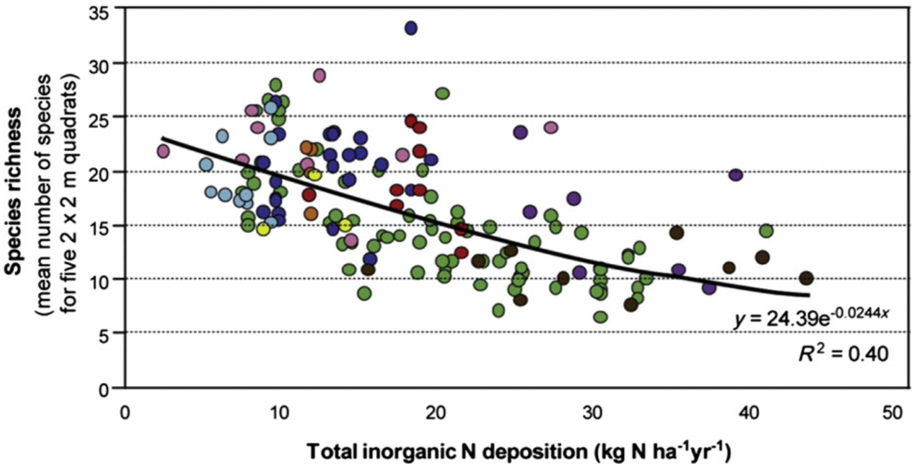

Figure 4 Nitrogen deposition reduces grassland biodiversity for x plots across Europe. Total plant species richness (mean number of species in five 2 × 2 m quadrats per site) against total inorganic N deposition for each of the countries surveyed: Belgium (red), Denmark (yellow), France (dark blue), Great Britain (green), Germany (brown), Ireland, Northern Ireland and Isle of Man (pink), the Netherlands (purple), Norway (turquoise), and Sweden (orange). The curvilinear relationship between N deposition and species richness is shown. From Stevens, C. J., and Coauthors, 2010: Nitrogen deposition threatens species richness of grasslands across Europe. *Environ. Pollut.*, **158,** 2940–2945.

challenging to estimate value, but the linkages are clear between biodiversity and key supporting ecosystem services. The provision of habitat for organisms which influence the integrity, resilience, spiritual value, and beauty of the natural world is an important service (e.g., Losey and Vaughan 2006). In addition, N-driven changes in biodiversity can influence nutrient losses and influence fire frequencies (Tilman et al. 1996; Rao et al. 2010), which have important economic and human health consequences.

Ecosystem acidification via atmospheric N deposition is another driver of species change. Sulfur deposition has also been an important driver of acidification and so this discussion includes the effects of both since they are so strongly related. Following deposition, sulfate and nitrate anions can leach out of soils, carrying with them an equivalent loss of base cations (K, Ca, and Mg) from the soil. Over prolonged periods, this leaching has negative consequences for the supporting service of soil fertility. Soil acidification can also lead to mobilization of inorganic Al (Reuss 1983) with detrimental effects on tree health, including aluminum interference with calcium uptake, cold tolerance, and aluminum toxicity to roots (Parker et al. 1989; Cronan and Grigal 1995). Low *p*H and inorganic monomeric Al are directly harmful to fish (Baker and Schofield 1982), and fishless lakes in the Adirondacks have significantly lower *p*H and ANC than lakes with fish (Gallagher and Baker 1990). Leaching of Al from soils into sensitive aquatic systems has also been shown to reduce fish diversity (Nierzwicki-Bauer et al. 2010). These acidity-driven shifts in fish abundance and diversity have implications for sport fishing and recreation, as well as cultural and nonuse values, such as use of religious sites or just the knowledge that these native ecosystems exist without human disturbance.

High rates of N loading to surface waters, through saturation of the ecosystem's ability to retain nitrogen (Aber et al. 1989) can contribute to excessive productivity, or eutrophication, characterized by algal blooms that prevent swimming, fish consumption and/or other human use (Van Dolah 2000), hypoxia (Breitburg et al. 2009), shifts in species composition (Vaas and Jordan 1990) and food webs, and water with unpleasant tastes and odors (Pretty et al. 2003). These factors negatively affect fish production, biodiversity, water quality, recreation potential, esthetics, and human health. Dodds et al. (2009) conservatively estimate that the costs of freshwater eutrophication, including costs to recreation, waterfront real estate, and spending on recovery of threatened and endangered species in the United States, are approximately $2.2 billion per year.

Nitrogen can also influence human experiences in nature, which are economically and socially important. Nitrogen is a component of regional haze, which can affect visibility and decrease esthetic enjoyment of places where people live, work, and recreate, including parks and other rural areas (Malm 1989). Visibility damages associated with reactive N in the Chesapeake Bay watershed were $120 million (Birch et al. 2011). Damage costs of HABs to recreation and tourism ranged from <$1 to $28 million (Hoagland et al. 2002). Damages by reactive N to recreational use within the Chesapeake Bay estuary were estimated to be $730 million per year (Birch et al. 2011). Other studies have estimated the value of improving the quality of natural resources by asking people what they are willing to pay. Banzhaf et al. (2006) estimated that New York state residents are willing to pay $45–100 each year to reduce the number of acidified lakes and improve forest health in the Adirondacks, which translates to $300–700 million for all state residents. These traditionally considered 'nonuse values' are an important component to human well-being and thus represent an important and increasingly well-quantified ecosystem service.

4.03.3.4 Climate Regulation

Nitrogen plays a key role in the maintenance of the climate system as a crucial regulating ecosystem service by influencing the production of several greenhouse gases (N_2O, CO_2, and CH_4) through its role as a mediator of aerosol production and due to its influence on biogeochemical processes. Human alteration of the N cycle affects the Earth's climate system via direct and indirect pathways. Nitrogen availability provides

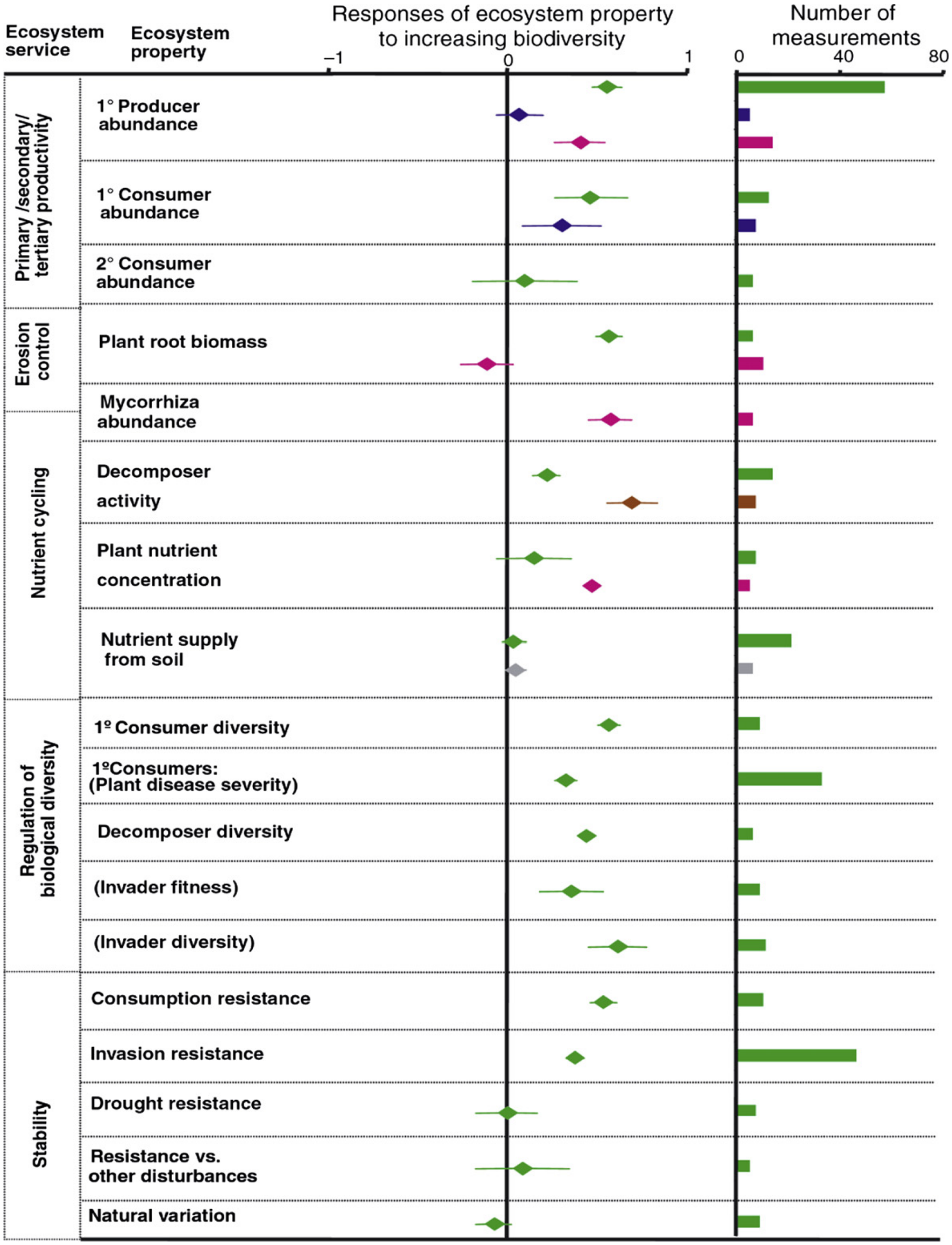

Figure 5 Meta-analysis of the magnitude and direction of biodiversity effects on ecosystem services. Shown are mean values and SE of normalized effect sizes and number of measurements available for ecosystem properties organized into ecosystem services. Colored bars show differential effects of trophic level manipulated: green, primary producers; blue, primary consumers; pink, mycorrhiza; brown, decomposer; gray, multiple trophic levels. Ecosystem properties shown in parentheses were considered of negative value for human well-being, and thus opposite of effect sizes are shown. From Balvanera, P., A. B. Pfisterer, N. Buchmann, J.-S. He, T. Nakashizuka, D. Raffaelli, and B. Schmid, 2006: Quantifying the evidence for biodiversity effects on ecosystem functioning and services. *Ecol. Lett.*, **9,** 1146–1156.

a fundamental constraint on plant growth and net CO_2 uptake across much of the world now and on response to rising atmosphere CO_2 concentrations in the future (Hungate et al. 2003). As discussed above, N inputs from atmospheric deposition can enhance plant growth rates and may account for a significant fraction of current terrestrial C uptake in some systems (Liu and Greaver 2009; Thomas et al. 2010). Furthermore, additions of N to some soils can inhibit decomposition, slowing release of CO_2 to the atmosphere, and leading to an increase in soil C stocks (e.g., Janssens and Luyssaert 2009).

However, net greenhouse benefits of C storage by some ecosystems may be somewhat dampened by the production of other greenhouse gases. In a meta-analysis, nitrogen additions were found to stimulate CH_4 production, decrease CH_4 uptake, and increase N_2O production (Liu and Greaver 2009). Atmospheric N_2O concentrations are rapidly increasing in response to N enrichment of terrestrial and aquatic systems and are presently 16% greater than during preindustrial times (Forster et al. 2007). Kusiima et al. (2010) identify several efforts to provide preliminary values of the anticipated impacts of greenhouse gases of approximately \$4–10 per ton of CO_2, equivalent to \$1.2–3.1 per kg N.

Nitrogen also influences the climate system through its link to ozone. In the lower atmosphere, N plays a key role in tropospheric ozone production (Skalska et al. 2010). In turn, ozone directly affects the climate system by acting as a greenhouse gas with roughly double the climate effect of N_2O (Forster et al. 2007), and indirectly through effects on photosynthesis and plant uptake of atmospheric CO_2. Ozone damage to plants, as discussed earlier in the section on production, may also decrease plant uptake of atmospheric CO_2 by as much as 14–23% (Sitch et al. 2007), leading to more CO_2-driven warming.

In addition to affecting the balance of greenhouse gases in the atmosphere, production of NO_x and NH_x increases the concentrations of atmospheric aerosols, which aside from their negative health effects can provide substantial cooling, both directly (due to high reflectivity) and indirectly (by mediating cloud formation). The influence of reactive N continues into the upper atmosphere, where ozone acts to provide a small amount of cooling. Current efforts are attempting to quantify the net impact of warming and cooling effects relative to reactive nitrogen (Davidson et al. 2012).

4.03.4 Current and Future Trends in N Deposition and Effects on Ecosystem Services: Recovery and Future Research Needs

Release of nitrogen to the atmosphere in the United States has substantially declined during the last few decades (Figure 6), and some of these changes will yield improvements in ecosystem services. The recovery might be most pronounced for those services that are quick to respond, such as those directly derived from the provision of clean air. For example, the 1990 Clean Air Act Amendments and subsequent programs have led to decreases in emissions of NO_x down by 67% in 2009 from 1995 levels. In the United States, these declines have meant less fine particles and ozone in the air, and in turn fewer deaths and hospital visits at an estimated benefit of \$170–430 billion per year (2008 dollars; Burns et al. 2011).

In areas of the northeastern United States where N deposition has declined, there has been a trend toward recovery of surface water chemistry reflected by increases in *p*H and acid neutralizing capacity and decreases in sulfate and to a lesser extent nitrate concentrations (Kahl et al. 2004; Driscoll et al. 2007). Other services may require longer time courses for recovery depending upon the mechanisms involved. Burns et al. (2011) suggest that changes in aquatic biology and terrestrial ecosystem recovery, while expected, have not been well documented since the reductions in N deposition. The loss of biodiversity can occur through a number of different mechanisms, but the driving mechanism was the accumulation and enrichment of ecosystems with N (Bobbink et al. 2010). Recovery was very slow after cessation of N inputs in a long-term grassland experiment, even with only small amounts of increases in N (Clark et al. 2009). Therefore, even though N deposition may have declined, recovery of biodiversity and other important components of ecosystem structure and function may lag behind if the driving mechanisms recover slowly.

4.03.5 Continued Science Needs in Understanding the Impacts of N Deposition on Ecosystem Services

The relative damage costs to different ecosystem services caused by nitrogen are shown in Figure 7. The most costly impacts relate to human health and also to recreation. However, there are many gaps in this analysis, most notably those associated with freshwater ecosystem services, including recreation and harmful algal blooms. Carpenter et al. (2009) call for improved monitoring of ecosystem services, which requires '(i) time series information on land cover and land use, (ii) locations and rates of desertification, (iii) spatial patterns and changes in freshwater quality, (iv) stocks, flows, and economic values of ecosystem services, (v) trends in human use of ecosystem services, and (vi) trends in components of human well-being (particularly those not traditionally measured).' These monitoring needs also apply to our understanding of N deposition effects. Since the benefits to people are best reflected by recreation and nonuse values, there is a need for more data and models linking deposition and these ecosystem services, in addition to the linked water quality indicators that are better studied. In addition, more intermediate connections, such as aquatic biota and terrestrial ecosystem recovery, including biodiversity and forest products, should be examined.

The analysis by Birch et al. (2011) serves as a model approach because it ties the approaches for to reductions to the benefits. They illustrate that the choice of intervention used to achieve N reduction has distinct consequences for ecosystem services and benefits to people. When considering N loading to the Chesapeake Bay watershed, N deposition is not the largest source. Yet, the currently available damage costs associated with atmospheric N emissions are much greater than the other measured costs, primarily due to the high value placed on damages to human health associated with particulate matter and ozone, that is, mortality and hospital visits due to respiratory illness. Air deposition effects were greatest in this analysis, in part because the cost data are available. Future efforts to connect science and policy should attempt to include other

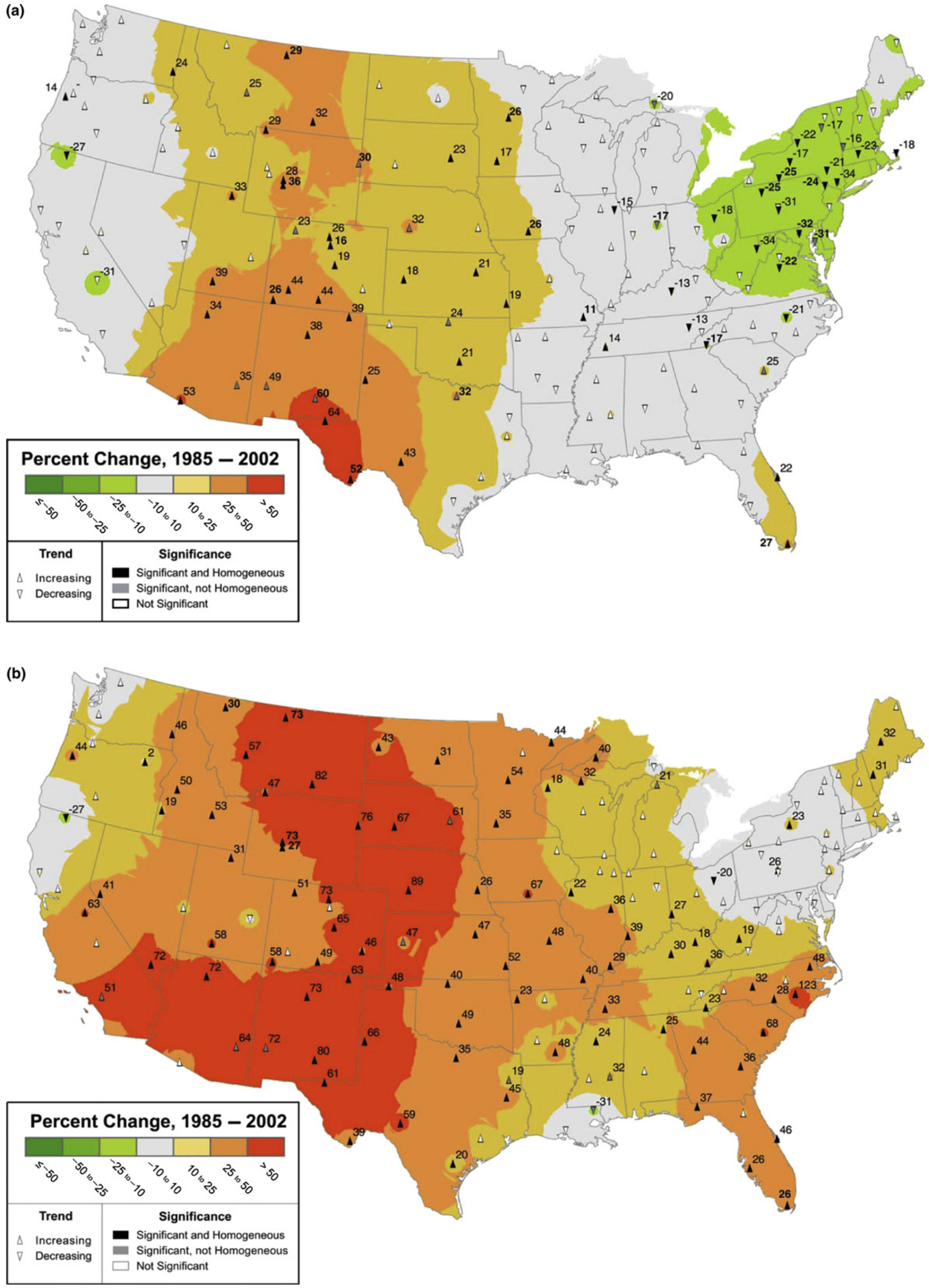
(a)
Percent Change, 1985 – 2002
≤–50
–50 to –25
–25 to –10
–10 to 10
10 to 25
25 to 50
> 50
Trend
Increasing
Decreasing
Significance
Significant and Homogeneous
Significant, not Homogeneous
Not Significant
(b)
Percent Change, 1985 – 2002
≤–50
–50 to –25
–25 to –10
–10 to 10
10 to 25
25 to 50
> 50
Trend
Increasing
Decreasing
Significance
Significant and Homogeneous
Significant, not Homogeneous
Not Significant

Figure 6 Changes in nitrate (a) and ammonium (b) concentrations in precipitation from 1985 to 2002. Current levels still exceed preindustrial levels in many areas. Reproduced from Lehmann, C. M. B., V. C. Bowersox, and S. M. Larson, 2005: Spatial and temporal trends of precipitation chemistry in the United States,1985–2002. *Environ. Pollut.*, **135,** 347–361.

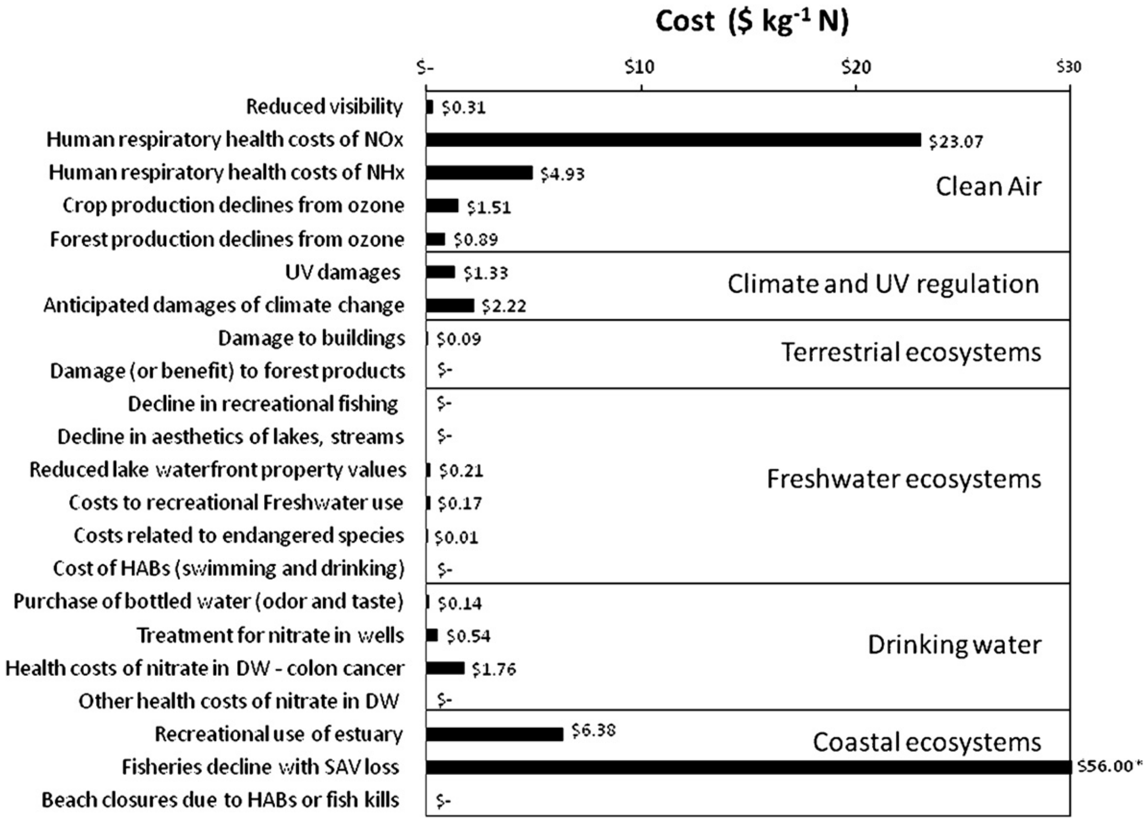

Figure 7 Range of damage cost estimates associated with nitrogen pollution. *One estimate of the cost of damages to coastal fish populations exceeded the scale of the graph. Based on Compton, J. E., J. A. Harrison, R. L. Dennis, T. L. Greaver, B. H. Hill, S. J. Jordan, H. Walker, and H. V. Campbell, 2011: Ecosystem services altered by human changes in the nitrogen cycle: a new perspective for US decision making. *Ecol. Lett.*, **14,** 804–815.

costs, for example, those associated with ozone-depletion, climate change, and freshwater costs, which are gaps in Figure 7. Quantification of ecosystem service impacts tied to the source can help decision-makers evaluate how to prioritize different interventions in the nitrogen cycle to move toward more efficient and sustainable N use.

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International Nitrogen Initiative – http://www.initrogen.org
US EPA's Ecosystem Services Research Program – http://www.epa.gov/ecology/

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4.04 Effects of Carbon Dioxide Enrichment on Plants

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Glossary

Biogeochemical Of or relating to the transfer and cycling of energy and materials among the living and nonliving components of ecosystems (such as organisms, soils, bodies of water, and the atmosphere).

Herbivore An animal that feeds on plants.

Herbivory The feeding of an animal on plants.

Legume A plant of the botanical family *Fabaceae*. Many legume species develop symbiotic relationships with bacteria that can fix (acquire) atmospheric nitrogen and make it available for incorporation into organic molecules.

Monoculture An ecological community in which all individuals are members of the same species.

Nonstructural carbohydrate A carbohydrate (starches and sugars) that does not comprise a component of plant cell wall structures. The term is used in comparison with structural carbohydrates, such as cellulose, which make up a large fraction of plant cell walls.

Stomata Small pores on the surfaces of plant leaves through which gases such as carbon dioxide and water vapor are exchanged between plant tissues and the external atmosphere.

Stomatal conductance A measure of the ability of a leaf surface to allow transfer of gases in and out through the stomata. This is closely related to the extent to which the stomata are open at a given moment.

Transpiration The movement of water vapor from a plant into the atmosphere. Takes place largely through stomata.

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4.04.1 Introduction

4.04.1.1 Increases in Atmospheric CO_2

Concentrations of carbon dioxide in Earth's atmosphere have been steadily increasing, from an average of approximately 280 ppm (parts per million) prior to the Industrial Revolution (Gerhart and Ward 2010), to approximately 315 ppm in 1959, to a current (2012) average of approximately 392 ppm (Conway and Tans 2012). Projections of concentrations for the year 2100 vary widely, but are mostly in the range of 500–1000 ppm (Solomon et al. 2007). These increases in atmospheric CO_2 concentrations have received a great deal of attention as a potential influence on climate. However, increasing atmospheric concentrations of CO_2 also directly affect biogeochemical processes that directly involve the carbon dioxide molecule including (1) effects on organisms that uptake CO_2 in photosynthesis, (2) decreasing ocean pH due to increased dissolution of CO_2 to form carbonic acid, (3) alterations in oceanic carbonate chemistry, with impacts on marine organisms with calcified body parts. In this review we will focus on direct CO_2 effects on terrestrial plants. We refer readers to Denman et al. (2011), Fabry et al. (2008), and Guniotte and Fabry (2008) for reviews of the effects of rising atmospheric CO_2 on ocean chemistry and marine organisms.

In this review, we first discuss the experimental methodology that has been used to discover the effects of growth under elevated concentrations of CO_2 on plants and plant communities. We then consider the various ways that increased atmospheric concentrations of CO_2 can affect plant growth, chemistry, and physiological functioning, and examine the impact of CO_2 enrichment on plant community structure and function. Finally, we examine ways that the effects of elevated CO_2 on plants may negatively impact the ecosystem services that plants provide. Throughout, it should be noted that we are concerned with the direct effects of increasing atmospheric CO_2 on plants rather than effects that may occur indirectly through the influence of rising atmospheric CO_2 on other aspects of the climate system.

4.04.1.2 Experimental Methodology of Elevated CO_2 Research

Our knowledge of the effects on plants of increased concentrations of atmospheric CO_2 comes from experiments in which plants have been artificially exposed to the CO_2 concentrations anticipated to occur over the next century (aka elevated CO_2 conditions). A wide range of facilities have been used to fumigate plants with elevated CO_2 in this manner. These facilities can be divided into three broad categories.

1. Closed facilities. These facilities include growth chambers, CO_2-controlled greenhouses, and other indoor facilities. Closed facilities have been used widely, and were the earliest technology used for CO_2 enrichment studies. One major advantage of these facilities is the ability to precisely control environmental conditions, including CO_2 concentration, temperature, light intensity, photoperiod, and relative humidity. Another advantage is a relatively low cost of operation. The chief drawback of these facilities is a lack of realism: plants are typically rooted in soil in pots that restrict root growth and environmental conditions inside these facilities can be quite different from field conditions.
2. Semi-open systems. This category is best represented by open-top chambers (OTC). These can be placed in natural and agricultural field settings. Plants in these experiments are often rooted naturally in the soil, and because the chambers have open tops, the environment is much closer to field conditions than inside enclosed facilities. However, plants grown in OTCs usually experience warmer, more humid conditions and lower light intensity than those grown outside (Kimball et al. 1997).
3. Free-air CO_2 enrichment (FACE). In FACE facilities, gas emitters are used to fumigate vegetation with gases such as CO_2 and ozone without enclosing chambers of any kind. FACE can therefore simulate changes in atmospheric composition under realistic field conditions. Because FACE rings are typically larger in size (up to 15–25 m diameter) than either enclosed facilities or OTCs, FACE facilities can also incorporate a large number of plants, and can be used to study ecosystem interactions that occur over somewhat larger spatial scales than for other methods of CO_2 enrichment. The shortcomings of FACE include a high cost of setup and maintenance, and problems maintaining steady CO_2 levels under windy conditions. All things considered, FACE offers the most realistic simulation of the real-world environmental conditions of the future. The first generation of FACE experiments have largely been completed, and researchers have recently been considering ambitious plans for new types of FACE experiments that could operate at even larger scales and with enhanced realism (Ainsworth et al. 2008; Calfapietra et al. 2009). In this article, we incorporate results from all types of CO_2-enrichment facilities, focusing on results from FACE experiments when available. Throughout, we identify the type of research facility from which particular results have been obtained, so the data can be interpreted in the proper context. If we do not specify a particular type of facility, we (or the previous authors we cite) are discussing results drawn from all types of facilities.

4.04.2 Effects of Elevated CO_2 on Plants

4.04.2.1 Physiological Effects

Plants assimilate carbon dioxide through the process of photosynthesis, chemically reducing the carbon to form organic molecules. These organic molecules make up more than 95% of the dry mass of a typical plant and provide energy for the plant's metabolism. Because CO_2 plays this pivotal role in plant metabolism, rising atmospheric CO_2 concentrations can be expected to alter a great many aspects of plant physiology and chemistry.

4.04.2.1.1 Photosynthesis and Growth

Plants grown under elevated CO_2 conditions typically experience increased rates of photosynthetic carbon fixation. Reviewing FACE studies performed on a broad range of plant species, Ainsworth and Rogers (2007) found an average increase in photosynthetic rates under elevated CO_2 (475–600 ppm) of 40%. The increased availability of reduced carbon compounds such as carbohydrates provided by this increased photosynthesis increases the growth rate for most plants. In FACE experiments, elevated CO_2 increased dry matter production of above-ground tissues by an average of 17% and production of below-ground tissues by more than 30% (Ainsworth and Long 2005; de Graaff et al. 2006). Norby and Zak (2011) found an average stimulation of net primary productivity (roughly defined as the amount of organic biomass entering an ecosystem through the photosynthetic organisms living there) of 23% in FACE experiments in forest ecosystems. Crop yields are also increased under elevated CO_2. Yields of wheat, rice, barley, and soybean increase by an average of 12–17% in FACE experiments (Ainsworth 2008; Ainsworth and McGrath 2010; Long et al. 2006). Yields of potato tubers increase even more, by ~30% on average (Ainsworth and McGrath 2010; Kimball 2010).

4.04.2.1.2 Transpiration and Water Use

Atmospheric concentrations of CO_2 can also affect plant water use. Carbon dioxide concentrations play a central role in controlling the aperture of stomata, small pores on the surfaces of plants, particularly on the underside of leaves. Open stomata provide a pathway for CO_2 to diffuse into leaves for photosynthesis, but also a pathway for water to diffuse out from leaves. Stomatal aperture (closely related to a physiological measure known as stomatal conductance) is therefore regulated to balance the goals of maintaining CO_2 assimilation and minimizing water loss. At higher concentrations of atmospheric CO_2, plants are able to achieve high rates of photosynthesis with relatively low stomatal conductance. In FACE experiments, elevated CO_2 decreases stomatal conductance by an average of 22% (Ainsworth and Rogers 2007).

Effects of elevated CO_2 on water use by whole plants or plant communities will depend not only on effects on stomatal conductance and leaf-level transpiration, but also on other potential effects of elevated CO_2, such as changes in plant size and morphology. For example, increased growth of plants may lead to increased numbers of leaves, offsetting decreased transpiration per leaf (Warren et al. 2011). Nonetheless, the overall effect of elevated CO_2 appears to be a decrease in total plant and ecosystem water usage, by approximately 5–20% in FACE experiments (Kimball 2010; Leakey et al. 2009). This can lead to alterations of ecosystem hydrology, including an increase in soil moisture and perhaps runoff (Leakey et al. 2009; Norby and Zak 2011).

4.04.2.1.3 Plant Chemical Composition

Growth of plants under elevated CO_2 conditions can affect the chemistry of plants in a number of ways. In FACE experiments, enhanced photosynthetic activity under elevated CO_2 leads to an increase, on average, of 30–40% in leaf nonstructural carbohydrates per unit leaf area (Ainsworth 2008; Ainsworth and Long 2005). Tissue concentrations of nitrogen (N), in contrast, typically decrease under elevated CO_2 (Cotrufo et al. 1998). Surveys of the research literature have found decreases in N concentrations averaging approximately 10–15% for leaves of woody plants (Curtis and Wang 1998; Norby et al. 1999), for leaves of all species under FACE conditions (Ainsworth and Long 2005), seeds (Jablonski et al. 2002), and stems and roots (Cotrufo et al. 1998).

Although the various literature surveys have found similar mean effects of elevated CO_2, effects in individual experiments vary in magnitude. In one survey, Norby et al. (1999) found that changes in leaf N concentration in leaves ranged from a decrease of 35% to an increase of 20%. Yin (2002) found an even greater range in the studies he reviewed from a 56% decrease to a 20% increase in leaf N.

The decreased concentrations of nitrogen typically observed under elevated CO_2 conditions appear to be, at least in part, directly tied to the increased plant concentrations of carbohydrates (Taub and Wang 2008). Carbohydrates are composed largely of carbon, hydrogen, and oxygen. Increasing concentrations of carbohydrates therefore increases the proportion of plant mass composed of these elements, while decreasing the proportion accounted for by other elements such as nitrogen.

Increased concentrations of nonstructural carbohydrates cannot fully account for the observed effects of elevated CO_2 on plant nitrogen. Poorter et al. (1997), in experiments with 27 plant species, found that growth at elevated CO_2 decreased leaf nitrogen concentrations by an average of 17%. When they recalculated after subtracting out nonstructural carbohydrates, the effect of elevated CO_2 was diminished, but there was a still-significant 10% decrease in N concentrations. Taub and Wang (2008) similarly found that, in various studies, 'dilution' by increased concentrations of carbohydrates could account for only a portion of the decrease in N under elevated CO_2.

In addition to carbohydrate dilution, a number of alternative physiological mechanisms have been suggested to contribute to the decreases in N concentrations (reviewed by Taub and Wang 2008, 2011). Of these, perhaps the best supported explanation is a decrease in transpirationally mediated N uptake. Water flowing through soil to plant roots carries dissolved minerals with it. Decreasing plant uptake of water caused by decreased stomatal conductance under elevated CO_2 can therefore potentially decrease uptake of mineral elements such as nitrogen (McDonald et al. 2002).

Although the effect of elevated CO_2 on mineral element concentrations has been best studied for nitrogen, it appears that plant concentrations of other minerals may also be decreased under elevated CO_2. Loladze (2002) suggested that plant concentrations of all elements other than carbon, hydrogen, and oxygen should be decreased under elevated CO_2. He also presented data suggesting that this was indeed the case for most mineral elements in both leaves and in wheat grains. The mechanism(s) responsible for decreasing concentrations of these elements may be similar to those for nitrogen. Dilution through carbohydrate accumulation would be expected to equally impact all elements except for C, H, and O (the elements that carbohydrates are composed of), and decreased uptake through decreased transpirational flow of water would be expected to impact all elements obtained through the soil, though to a degree that would differ depending on properties affecting the interactions of particular mineral ions with soils.

4.04.2.2 Effects of Other Environmental Factors on Plant Responses to Elevated CO_2

In the foregoing discussion, we have focused on the average effects of CO_2 enrichment on growth and physiology of plants across all types of environmental conditions. However, the effects of elevated CO_2 on plants interact with those of other environmental factors, most notably soil water, soil fertility, air temperature, and ozone pollution.

4.04.2.2.1 Soil Water

Water availability is of primary importance to plant growth and affects growth responses to elevated CO_2 (Curtis and Wang 1998; Idso and Idso 1994; Körner 2003; Poorter and Perez-Soba 2001; Wullschleger et al. 2002). Plants do not grow well when water is limited, regardless of CO_2 concentration. However, CO_2 enrichment is able to alleviate the negative effect of drought stress on plant growth because plants can close their stomata (small openings on leaf surface) and still let in sufficient CO_2 for photosynthesis. In addition, plants grown under water stress allocate more biomass belowground and develop more extensive root systems (Curtis et al. 1990; Idso et al. 1988; Wang and Taub 2010). As a result, the relative responsiveness to elevated CO_2 in biomass production is typically higher in drier soil than under well-watered conditions, although the absolute biomass production will be lower (Idso and Idso 1994).

4.04.2.2.2 Soil Fertility

Although elevated CO_2 makes carbon more abundant and available for photosynthesis, plants require other resources to fully take advantage of this additional carbon, including a variety of minerals obtained from the soil. Not only does elevated CO_2 not make these soil-derived mineral elements more available, it may even decrease their uptake under certain conditions (see Section 2.01.3 Vulnerabilities; Taub and Wang 2008). Under conditions of low soil fertility, plants may therefore experience diminished ability to increase photosynthesis and growth in response to elevated CO_2. This effect has been particularly noted for nitrogen. Photosynthesis and crop yield are enhanced by elevated CO_2 less under low soil N condition than under high soil N in FACE experiments (Ainsworth 2008; Ainsworth and Long 2005; Ainsworth and Rogers 2007; Long et al. 2006). Biomass production is enhanced by elevated CO_2 less under low nutrient conditions than high nutrient conditions across studies using all types of CO_2 enrichment technology (Idso and Idso 1994; Poorter and Navas 2003).

4.04.2.2.3 Air Temperature

Temperature records in many localities of the world have shown warming trends and rising CO_2 concentrations in the atmosphere have the potential to enhance these trends (Solomon et al. 2007). Within a certain temperature range, increases in temperature increase the photosynthetic rate of green plants (Farquhar et al. 1980). The photosynthetic temperature optimum, the temperature at which photosynthesis is maximal, generally increases with rising CO_2 level (Berry and Bjorkman 1980; Long 1991; McMurtrie and Wang 1993). Higher temperatures therefore tend to amplify the enhancing effect of CO_2 enrichment on plant growth.

4.04.2.2.4 Ozone Pollution

Ozone gas (O_3) exists both in earth's upper atmosphere (where it is vital to our well-being due to its absorption of ultraviolent radiation) and at ground level where it is largely a toxic by-product of air pollution. Ground-level concentrations of O_3 worldwide are steadily increasing due to increased emissions of chemicals that react to produce ozone (Vingarzan 2004). Ozone at high concentrations causes damage to the internal tissues of leaves, leading to decreased photosynthesis and growth (Feng et al. 2008; Morgan et al. 2003). However, plants grown under elevated CO_2 typically decrease openness of stomata (see Section 2.01.2; Curtis and Wang 1998; Medlyn et al. 2001) and can therefore decrease exposure of internal leaf tissues to O_3. Enhancement of plant growth by elevated CO_2 is typically much greater when plants are stressed by high O_3 concentrations than otherwise (Poorter and Navas 2003). Growth under elevated CO_2 has also been shown to decrease the negative effects of high O_3 on photosynthesis, growth, and seed production in several crop species (Feng et al. 2008; Morgan et al. 2003). There is also evidence that elevated levels of CO_2 and O_3 interact in affecting plant biomass allocation. Wang and Taub (2010) found that plants grown under elevated CO_2 and elevated O_3 increased allocation of biomass belowground compared to those grown under ambient conditions. This altered allocation of biomass at elevated O_3 may have important implications for the global carbon cycle because biomass below-ground differs greatly from biomass aboveground in terms of the length of time carbon is sequestered away from the atmosphere.

4.04.2.3 Differences among Plants in Responses to Elevated CO_2

4.04.2.3.1 Variation in Photosynthetic Processes and Responses to Elevated CO_2

Previously, we have discussed the average effects of growth under elevated CO_2 across all species of plants. However there are important differences in response to CO_2 among different types of plants. Perhaps the two most important determinants of plant species' responses to elevated CO_2 are (1) the variant of photosynthetic physiology that a species uses and (2) whether the species is a legume.

There are several major variants of photosynthetic physiology found in land plants. The great majority of plant species (~90%) use the photosynthetic mechanism known as C_3 photosynthesis. The other photosynthetic variants, known as CAM and C_4 photosynthesis, have evolved as elaborations from C_3 photosynthesis. Although a greater number of species use CAM than C_4 photosynthesis, C_4 plants are probably of greater ecological importance, as this type of physiology is found in the majority of grass species that are the dominant vegetation throughout tropical and subtropical grasslands and savannahs (Sage et al. 1999). Additionally, while there is only one CAM species of major agronomic importance (pineapple), the C_4 mechanism is used by a number of important crop species, including maize, sorghum, sugar cane, and the various millet species. Corresponding with these differences in ecological and economic importance, there has been considerably more research performed on responses to elevated CO_2 for C_4 species than for CAM species.

Plants that utilize the C_4 variant of photosynthesis biochemically concentrate CO_2 in specialized bundle sheath cells within the leaf. For C_4 species, it is within these cells that the incorporation of CO_2 into organic compounds by the Calvin photosynthetic cycle takes place. Because the plants already concentrate CO_2 within the bundle sheath cells, C_4 species experience little increase in photosynthetic rates from increasing atmospheric CO_2 concentrations above the current ambient. Stomatal conductance does decrease under elevated CO_2, much as with C_3 species. Under conditions of drought this may alleviate some of the effects of water stress, indirectly leading to higher photosynthetic rates and increased growth under elevated than ambient CO_2 conditions (Kimball 2010; Leakey et al. 2009). Overall, in FACE experiments, C_4 plants show approximately one-third of the increase of photosynthetic rates experienced by C_3 species, and little enhancement of growth (Ainsworth and Long 2005). There also appears to be little or no increase in grain yields for C_4 crops under elevated CO_2 in FACE studies (Ainsworth and McGrath 2010; Long et al. 2006). C_4 plants also show much less of a response of nitrogen and protein concentrations to elevated CO_2 than do C_3 plants (Cotrufo et al. 1998). In most respects, therefore, C_4 plants can be expected to be less responsive than C_3 plants to increasing atmospheric CO_2.

4.04.2.3.2 Responses to Elevated CO_2 in Legumes

In contrast to the relative unresponsiveness of C_4 species to elevated atmospheric CO_2, legumes (plants of the botanical family *Fabaceae*; all perform C_3 photosynthesis) respond particularly strongly with increased photosynthesis and growth (Rogers et al. 2009). As we have discussed, for most plants elevated CO_2 alters the balance between internal concentrations of carbon and nitrogen. Legumes, however, form symbiotic relationships with bacteria that live in nodules on the plant's roots. These bacteria are capable of a process known as nitrogen fixation, in which atmospheric nitrogen is chemically reduced to a form in which it can enter into metabolism by the bacterium or plant and become incorporated into molecules such as proteins and nucleic acids. When grown under elevated CO_2, legumes may be able to direct carbohydrates obtained through enhanced photosynthesis to the root nodules. There the carbohydrates can provide a carbon and energy source for the nitrogen-fixing bacteria. When other nutrients are not limiting, legumes often experience increases in fixation of nitrogen by their bacterial symbionts under elevated CO_2 (de Graaff et al. 2006; Lee et al. 2003; Rogers et al. 2009; Schortemeyer et al. 2002; Zanetti et al. 1996). Being able to exchange carbon for nitrogen in this way may enable legumes to maximize the beneficial effects of elevated CO_2, and obtain greater enhancement of photosynthesis and growth than shown by most other plant species (Rogers et al. 2009). In addition, the greater availability of nitrogen often prevents at least some of the decrease in nitrogen concentrations seen in other plants grown under elevated CO_2. Cotrufo et al. (1998) reviewing evidence from a large range of studies found an average decrease in tissue nitrogen concentrations in legumes of 7%, compared to 16% for C_3 plant species lacking N-fixing symbionts. Jablonski et al. (2002) found no decrease in nitrogen concentrations under elevated CO_2 in the seeds of legumes, compared to an average decrease of 14% in the seeds of nonlegume C_3 plants.

4.04.2.3.3 CO_2 Responses in Crops versus Wild Species

Populations of wild and crop species provide additional insight on the responsiveness of plant growth under CO_2 enrichment in different plants. Wild and crop species are different in many ways, particularly in the traits that have been subject to intensive selection by humans. As a result, wild and crop species respond differently to CO_2 enrichment in growth and reproduction (Figure 1). Crops both allocate a larger proportion of biomass to reproduction than wild species and respond more in fruit and seed production than wild species to CO_2 enrichment (Jablonski et al. 2002). Biomass production is enhanced to a greater extent in crops than wild species

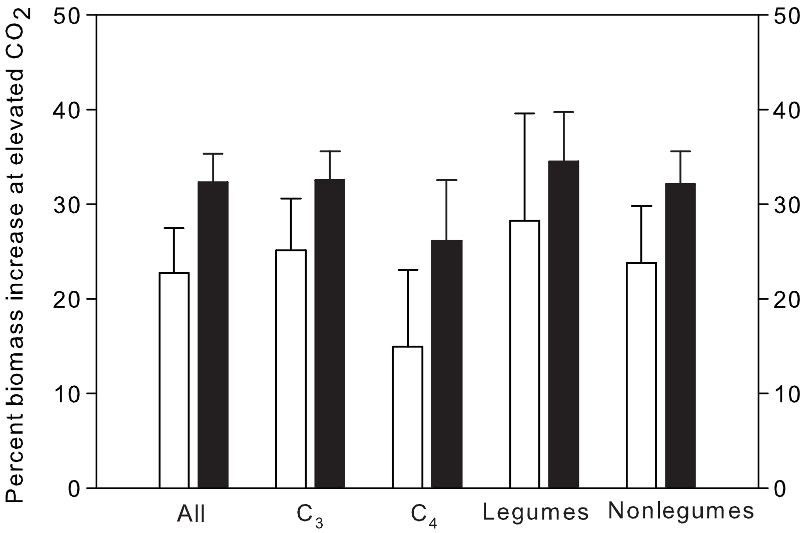

Figure 1 Percent increase in total biomass production of herbaceous wild (unfilled bars) and crop (filled bars) species grown at elevated CO_2. Mean ± 95% confidence interval. For better comparison, only nonlegumes that are C_3 species are included in the analysis because all legumes are C_3 species. A number of studies for the response variables for ambient and elevated CO_2 are 186 and 334 (all), 143 and 323 (C_3), 43 and 11 (C_4), 43 and 54 (legumes), and 100 and 269 (nonlegumes).

(Wang et al. 2008), although the magnitude of response differs among plant functional groups (i.e., C_3 vs. C_4 species and legumes vs. nonlegumes; **Figure 1**). It should be noted that the results synthesized in Wang et al. (2008) were from monocultures. The effects of CO_2 enrichment may be different for plants when they are grown in competition with plants of different species.

4.04.2.4 Effects of Elevated CO_2 on Plant Communities

4.04.2.4.1 Responses to Elevated CO_2 in Monocultures versus Mixed-Species Communities

The effect of CO_2 enrichment on plant biomass production has been found to be different among different types of plant communities. For example, monocultures (plant communities composed of individuals of a single species) and mixed-species communities (plant communities composed of individuals of different species) differ in their responsiveness to CO_2 enrichment in terms of biomass accumulation. The magnitude of responsiveness is primarily determined by the responsiveness of the species themselves to CO_2 enrichment and by the ratio of the more to less responsive plant species in the community.

Results from a FACE study on grassland species showed that growth responsiveness to CO_2 enrichment was greater in mixed-species communities than in monocultures, suggesting that greater species richness would increase plant productivity responsiveness to elevated CO_2 (Reich et al. 2001, 2004). One mechanism that was proposed to explain the difference between monocultures and mixed-species communities was niche complementarity, that the use of resources differed among species and therefore allowed more efficient use of limited resources when there are multiple species in a community. A synthesis of a great number of independent studies by multiple researchers using various CO_2 exposure facilities, however, found that effects of elevated CO_2 on plant growth were generally less pronounced in mixed-species communities than in monocultures (Wang 2007). This pattern of greater responsiveness in monocultures was consistent across different growth forms and functional groups of plants, although the magnitude of response was dependent on other environmental factors, particularly soil nitrogen (Wang 2007). Although resource complementarity in mixed-species communities would be expected to increase responsiveness to elevated CO_2, there may be other factors that counteract the positive effects of resource complementarity (Wang 2007). In some mixed-species communities, plant species that are relatively unresponsive to elevated CO_2 may utilize a large share of limited resources, but contribute little to the overall biomass production of the community. If this mechanism, known as resource usurpation, is more dominant than niche complementarity in a community, plant production will respond less to CO_2 enrichment than in a monoculture of a responsive species. Based on a survey of the relevant research literature, this seems to be most generally the case (Wang 2007). Because plants grow in mixed-species communities under most real-world conditions, estimates of the effects of a CO_2 enriched environment on plant productivity derived from the numerous monoculture experiments that have been performed may have been overly optimistic.

4.04.2.4.2 Changes in Species Composition

Plant species not only differ in their responses to elevated CO_2, but also can alter the responsiveness of neighboring species to CO_2 enrichment. In some cases, a species that responds positively to CO_2 enrichment when grown as isolated individual plants or in monoculture will actually show decreased growth under elevated CO_2 in a mixed-species community (Poorter and Navas 2003). This will occur when the direct benefits of the elevated CO_2 are outweighed by increased competition from neighboring species that experience a greater stimulation of growth from the elevated CO_2. Increased atmospheric concentrations of CO_2 may therefore change the species composition of plant communities, as some species benefit more from elevated CO_2 than others. In experiments in mixed-species communities, C_4 plants often decrease as a proportion of total plant biomass under elevated CO_2, probably because the photosynthetic capacity of C_4 plants is saturated at a lower CO_2 concentration than it is for C_3 plants. Conversely, in mixed-species communities, legumes typically increase as a proportion of total biomass under elevated CO_2 (Poorter and Navas 2003). This is a result of legumes' ability to take fuller advantage of the increased CO_2 because their bacterial symbionts can convert atmospheric nitrogen, which cannot be used directly by nonlegumes as a nutrient, into a usable form of nitrogen. Other environmental factors will also interact with CO_2 enrichment in shaping community structure in a higher CO_2 environment, because species differ in their response and tolerance to these other effects, such as drought, elevated ozone, and higher temperature (Ainsworth and Long 2005; Bazzaz and Carlson 1984; Curtis and Wang 1998; de Graaff et al. 2006; Idso and Idso 1994; Kimball 1983). For example, Morgan et al. (2011) in a FACE experiment in a semiarid grassland community found that responses to elevated CO_2 in the biomass of C_3 and C_4 grasses varied among years, depending on the amount of precipitation during the growing season. They also found that C_4, but not C_3, grasses showed a positive biomass response to the combination of elevated CO_2 and experimentally increased temperature.

4.04.3 Potential Threats to Ecosystem Services from Elevated CO_2

4.04.3.1 Introduction

From a human vantage, the effects of increasing atmospheric CO_2 on plants may have both positive and negative influences on ecosystem services. Increases in the harvestable yield of many crops (Ainsworth 2008; Ainsworth and McGrath 2010; Long et al. 2006), for example, may be regarded as a significant benefit of increased CO_2 (note that the direct positive effects of elevated CO_2 on yield may be negated by effects of changes in weather patterns including temperature on crop yields; e.g., Lobell et al. 2011; Schlenker and Roberts 2009). However, in this section we focus on possible threats to ecosystem services from increasing atmospheric CO_2, rather than possible benefits. We do this not to suggest that negative effects predominate, but because these are the effects for which preventative, adaptive, or ameliorative actions may be required.

4.04.3.2 Effects on Human and Animal Nutrition

4.04.3.2.1 Decreases in Protein and Mineral Concentrations in Food Crops

A major concern with decreasing concentrations of nitrogen and other mineral elements in plant tissues is the potential impact on human nutrition. Nitrogen concentrations are particularly important in this regard. The amino acids that proteins are made of incorporate nitrogen in their chemical structures, and availability of nitrogen exerts a control on plant synthesis of proteins. Total nitrogen concentration in plant tissues is therefore closely related to protein concentration; indeed, the most commonly used analytical chemistry methods for measuring protein in crops actually involve measurement of plant nitrogen (e.g., AOAC 1990). The decreased concentrations of nitrogen observed in plants under elevated CO_2 therefore indicate decreased protein concentrations.

Taub et al. (2008) synthesized the experimental evidence on the effects of growth under elevated CO_2 on protein concentrations in the edible portions of major food crops. Decreases averaging approximately 10–15% were seen in the grains of wheat, rice, barley, and in potato tubers. For soybean, a legume, the decrease in seed protein concentration averaged only 1.3%.

This effect of elevated CO_2 on crop protein concentrations can vary with other environmental factors. For wheat, the effect of elevated CO_2 is decreased, but not eliminated, under conditions of high nitrogen fertility (**Figure 2**). Although similar data are not as readily available for other crops, the physiology of plant responses to nitrogen and CO_2 suggest that this should hold true for other nonlegume crops as well. Protein concentrations in potatoes are decreased by CO_2 more under high atmospheric concentrations of ozone (a toxic gas that is also increasing in concentration in the atmosphere near the earth's surface) than under low concentrations (**Figure 2**).

Decreases in grain protein under elevated CO_2 have been seen consistently across experiments that employed a wide range of crops, crop cultivars, environmental conditions, and experimental techniques (**Figure 3**). This suggests that decreasing crop protein concentrations under elevated CO_2 are a robust finding, likely to apply in the real-world elevated CO_2 conditions of the next century. However, because the magnitude of the CO_2 effect varies with environmental factors such as N and ozone and across experiments using different CO_2-enrichment technologies, it is difficult to estimate a precise magnitude for the average decrease in protein concentrations that will be seen under the real-world agricultural conditions of the next century.

The decreases in protein concentrations under elevated CO_2 that have been well-documented for wheat, rice and barley are likely to hold for other C_3 cereal crops, such as rye and oats (**Figure 4**, also Sæbø and Mortensen 1996). Similarly the decreases observed in potato tuber protein may also be found in other root crops (**Figure 4**, also Lu et al. 1986). On the other hand, the limited data on grain protein under elevated CO_2 for C_4 cereals such as maize and the millets shows little, if any,

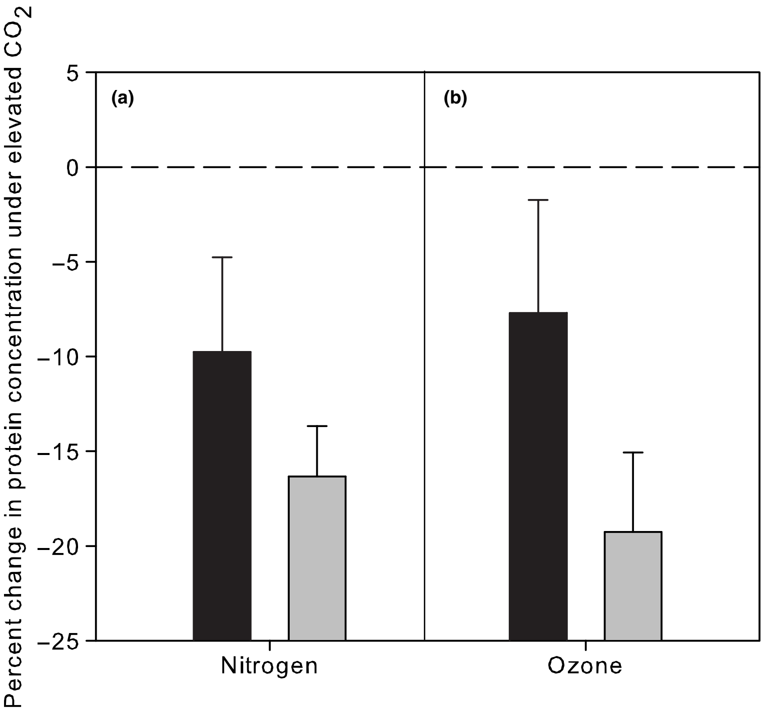

Figure 2 Effects of other environmental factors on the response of crop protein concentrations to elevated CO_2. (a) Effect of nitrogen supply on response of wheat protein concentration to CO_2 ($n = 15$). Dark bars: high N supply, light bars: low N supply. (b) Effect of ozone on response of potato protein concentration to CO_2 ($n = 7$). Dark bars: low atmospheric ozone concentrations, light bars: high atmospheric ozone concentrations. All data are taken from experiments that examined the effect of elevated CO_2 at both high and low N or high and low ozone. Means and 95% confidence intervals. Based on reanalysis of data from Taub, D., B. Miller, and H. Allen, 2008: Effects of elevated CO_2 on the protein concentration of food crops: a meta-analysis. *Glob. Change Biol.*, **14,** 565–575.

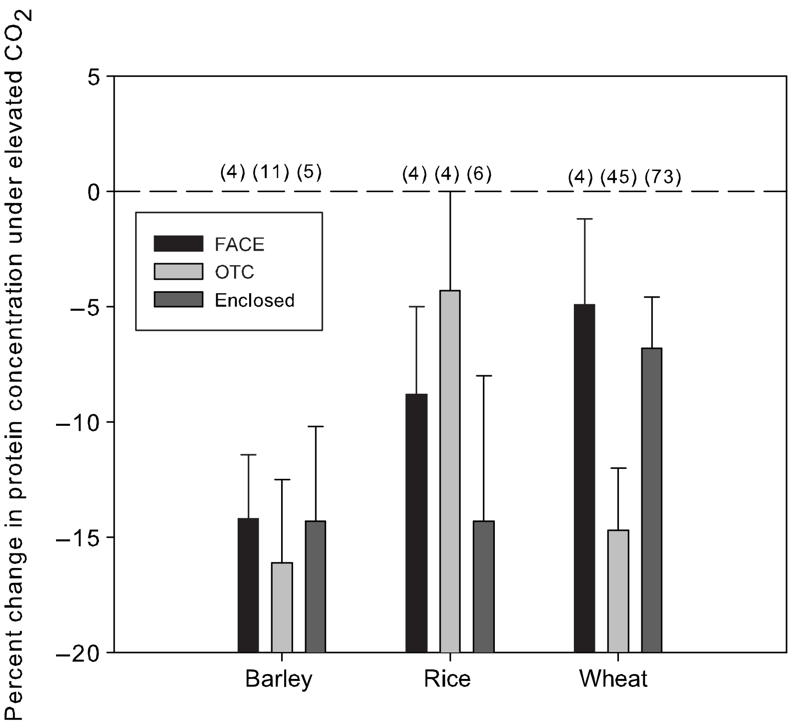

Figure 3 Effect of growth under elevated CO_2 on crop protein concentrations in experiments using different methods of CO_2 fumigation. Means and 95% confidence intervals. Number of experimental observations in parentheses. FACE, free-air carbon dioxide enrichment; OTC, open-top chambers; see text for description of fumigation technologies. Based on reanalysis of data from Taub, D., B. Miller, and H. Allen, 2008: Effects of elevated CO_2 on the protein concentration of food crops: a meta-analysis. *Glob. Change Biol.,* **14,** 565–575.

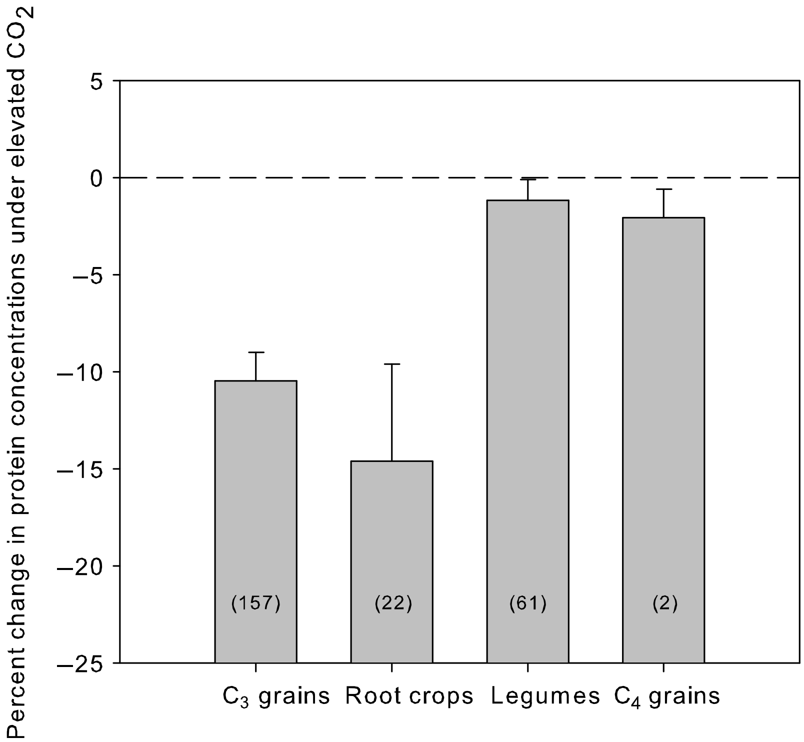

Figure 4 Effect of growth under elevated CO_2 on protein concentrations in several important crop types. Data on C_3 grains include studies on wheat, rice, barley, and oats. Data on root crops include studies on potato, sweet potato, and radish. Data on legumes include studies on soybean, peanut, cowpea, and fava bean. Means and 95% confidence intervals. Number of experimental observations in parentheses. Analysis expands on that of Taub, D., B. Miller, and H. Allen, 2008: Effects of elevated CO_2 on the protein concentration of food crops: a meta-analysis. *Glob. Change Biol.*, **14,** 565–575.

effect on grain protein concentrations (Figure 4; also Rogers et al. 1983). It also appears that the relatively modest effect of elevated CO_2 on protein concentrations in soybean may also hold for other legume crops (Figure 3; also Mbikayi et al. 1988; Rogers et al. 2009; Wolf 1996).

4.04.3.2.2 Effects of Elevated CO_2 on Human Dietary Protein

Human dietary protein is obtained from a variety of sources, including animal products, as well as a variety of plant foods, particularly legumes and grains, and in some cases root crops. Considering that C_3 grains and root crops appear to be particularly affected in protein concentration, we may expect dietary protein intake to be affected by elevated CO_2 to the extent that a particular population relies on these foods as sources of protein.

We have calculated for 173 nations the proportion of total dietary protein (from both plant and animal sources) comprised of C_3 grains and root crops (c.f. Taub and Wang 2011).

Worldwide, nearly 40% of human dietary protein is obtained directly from these types of crops (Table 1). This proportion varies widely among nations, from a low of 4.9% for Burkina Faso to a high of 76.8% for Bangladesh. For 27 nations, mostly in Asia and North Africa, more than half of total dietary protein is derived directly from C_3 grains and root crops. In contrast, for 19 nations, mostly in sub-Saharan Africa and Latin America, less than 20% of total dietary protein is derived from such sources. These appear mostly to be nations with a strong dietary reliance on C_4 grains (maize, sorghum, and the millets).

There are much less data available on the effects of elevated CO_2 for crop mineral concentrations than there for protein. Loladze (2002) lamented the scarcity of such data even for the major staple crops rice and wheat. His synthesis of the limited data available for wheat grains did show average decreases in concentrations of approximately 10–20% for most mineral

Table 1 Contributions of C_3 grains and root crops to total human dietary protein, by nation. These crop types are particularly liable to decreased protein concentrations as atmospheric concentrations of carbon dioxide increase (see text). Total protein includes both plant and animal sources. Nations deriving 50% or more of dietary protein from C_3 grains and root crops are shown in bold. Data calculated from FAO Food Balance sheets for 2003

	Percent of human dietary protein		
	C_3 grains	*Root crops*	*C_3 grains + root crops*
Albania	39.5	1.4	40.9
Algeria	**59.8**	**2.6**	**62.4**
Angola	17.5	14.9	32.4
Antigua and Barbuda	22.3	0.9	23.2
Argentina	27.6	3.3	31.0
Armenia	**50.2**	**5.2**	**55.5**
Australia	23.4	2.1	25.4
Austria	21.6	2.2	23.8
Azerbaijan	**61.1**	**4.0**	**65.1**
Bahamas	19.2	1.0	20.2
Bangladesh	**74.8**	**2.0**	**76.8**
Barbados	21.1	3.2	24.3
Belarus	32.0	8.8	40.7
Belgium	24.6	3.9	28.6
Belize	25.6	1.5	27.1
Benin	9.8	16.6	26.4
Bermuda	17.5	1.1	18.6
Bolivia	26.0	7.8	33.8
Bosnia and Herzegovina	24.0	0.0	24.0
Botswana	17.0	4.0	20.9
Brazil	21.2	1.9	23.1
Brunei	29.2	0.8	30.0
Bulgaria	34.9	1.6	36.5
Burkina Faso	4.7	0.2	4.9
Burundi	3.1	14.0	17.1
Cambodia	**57.7**	**0.6**	**58.3**
Cameroon	13.1	7.4	20.5
Canada	21.3	3.8	25.1
Cape Verde	25.9	2.0	27.9
Central African Republic	6.2	13.0	19.3
Chad	5.5	3.1	8.6
Chile	33.0	3.3	36.3
China	32.7	3.3	36.0
Columbia	20.1	5.6	25.6
Comoros	31.1	6.3	37.4
Congo, Dem Republic of	12.1	22.2	34.4
Congo, Republic of	33.5	11.0	44.5
Costa Rica	29.7	1.6	31.3
Cote d'Ivoire	28.7	14.7	43.3
Croatia	31.3	5.7	37.0
Cuba	30.4	2.8	33.2
Cyprus	20.3	1.1	21.4
Czech Republic	26.3	3.1	29.4
Denmark	23.1	2.7	25.8
Djibouti	**56.4**	**0.7**	**57.2**
Dominica	21.2	4.9	26.1
Dominican Republic	30.3	2.0	32.3
Ecuador	28.2	2.5	30.6
Egypt	43.4	0.8	44.1
El Salvador	12.2	1.6	13.8
Eritrea	**48.3**	**2.0**	**50.4**
Estonia	25.5	5.3	30.8
Ethiopia	26.0	4.8	30.8
Fiji Islands	39.1	5.1	44.2
Finland	26.4	3.1	29.5
France	21.2	2.4	23.6
French Polynesia	19.3	1.8	21.1
Gabon	25.8	7.8	33.5
Gambia	26.1	0.4	26.6
Georgia	43.6	3.5	47.1
Germany	25.0	3.1	28.1
Ghana	12.2	23.5	35.7
Greece	28.2	2.3	30.5
Grenada	19.0	2.0	21.0
Guatemala	15.3	0.5	15.8
Guinea	37.4	7.2	44.6
Guinea-Bissau	**47.9**	**4.5**	**52.4**
Guyana	35.0	1.8	36.8
Haiti	41.4	3.7	45.1
Honduras	14.8	0.4	15.2
Hungary	31.3	3.1	34.4

(*Continued*)

Table 1 Contributions of C_3 grains and root crops to total human dietary protein, by nation These crop types are particularly liable to decreased protein concentrations as atmospheric concentrations of carbon dioxide increase (see text). Total protein includes both plant and animal sources. Nations deriving 50% or more of dietary protein from C_3 grains and root crops are shown in bold. Data calculated from FAO Food Balance sheets for 2003—cont'd

	Percent of human dietary protein		
	C_3 grains	*Root crops*	*C_3 grains + root crops*
Iceland	19.9	1.6	21.5
India	**49.8**	**1.4**	**51.3**
Indonesia	45.5	1.8	47.2
Iran	**61.5**	**1.8**	**63.3**
Ireland	20.2	3.9	24.1
Israel	26.9	1.7	28.6
Italy	31.1	1.5	32.6
Jamaica	35.8	5.1	41.0
Japan	23.1	1.0	24.1
Jordan	30.7	0.8	31.5
Kazakhstan	42.4	3.2	45.6
Kenya	12.1	3.9	16.0
Kiribati	29.4	6.3	35.7
Korea, Dem People's Rep	30.7	5.0	35.7
Korea, Republic of	29.7	0.6	30.3
Kuwait	35.7	1.2	36.9
Kyrgyzstan	**54.8**	**5.9**	**60.7**
Laos	**56.5**	**1.4**	**57.9**
Latvia	30.0	7.3	37.3
Lebanon	29.9	3.3	33.2
Lesotho	15.0	2.9	17.9
Liberia	**49.1**	**13.9**	**63.1**
Libya	**52.7**	**1.3**	**54.0**
Lithuania	31.5	4.7	36.1
Macedonia, FYR	31.6	3.0	34.6
Madagascar	**49.1**	**8.5**	**57.6**
Malawi	3.5	9.1	12.6
Malaysia	33.2	0.7	33.8
Maldives	20.5	1.4	21.9
Mali	20.5	0.6	21.1
Malta	32.3	1.9	34.3
Mauritania	40.3	0.4	40.7
Mauritius	39.8	1.0	40.8
Mexico	9.4	0.7	10.1
Moldova	23.9	4.5	28.5
Mongolia	30.2	1.8	32.0
Morocco	**59.8**	**1.9**	**61.7**
Mozambique	17.7	15.9	33.7
Myanmar	**56.7**	**0.5**	**57.2**
Namibia	11.6	8.3	20.0
Nepal	45.7	3.7	49.4
Netherlands	23.6	3.4	27.0
Netherlands Antilles	26.2	2.5	28.8
New Caledonia	26.0	3.0	29.0
New Zealand	22.2	3.3	25.5
Nicaragua	18.2	0.7	19.0
Niger	7.5	0.5	8.1
Nigeria	15.1	8.7	23.7
Norway	27.9	3.1	31.0
Pakistan	44.3	1.0	45.3
Palestine	**50.7**	**1.2**	**51.8**
Panama	25.4	1.6	27.0
Paraguay	8.9	3.6	12.4
Peru	33.6	7.8	41.5
Philippines	43.5	1.2	44.7
Poland	35.3	5.7	41.0
Portugal	24.2	4.5	28.7
Romania	36.3	3.7	40.1
Russian Federation	36.9	6.0	42.9
Rwanda	3.1	22.9	26.0
Saint Kitts and Nevis	19.0	1.6	20.6
Saint Lucia	21.8	3.0	24.8
Saint Vincent, Grenadines	30.3	3.3	33.6
Samoa	18.1	7.0	25.1
Sao Tome and Principe	34.5	10.6	45.0
Saudi Arabia	37.3	0.6	37.9
Senegal	36.0	0.9	36.9
Serbia and Montenegro	20.7	2.3	22.9
Seychelles	23.4	0.5	23.9
Sierra Leone	43.0	4.6	47.6
Slovakia	35.0	4.0	39.0
Slovenia	21.5	2.1	23.6
Solomon Islands	**29.9**	**23.9**	**53.8**
South Africa	19.8	1.4	21.2
Spain	19.8	2.9	22.7
Sri Lanka	**50.8**	**0.8**	**51.6**
Sudan	12.8	0.3	13.1
Suriname	40.9	1.9	42.8
Swaziland	23.1	3.8	26.9
Sweden	21.5	2.0	23.5
Switzerland	23.5	2.0	25.6
Syria	47.5	1.0	48.5
Tajikistan	**67.6**	**5.3**	**72.8**
Tanzania	11.4	9.0	20.4
Thailand	36.8	0.8	37.5
Timor-Leste	34.1	5.3	39.4
Togo	14.6	13.1	27.7
Trinidad and Tobago	34.8	2.5	37.3
Tunisia	**54.1**	**1.3**	**55.3**
Turkey	**49.4**	**2.8**	**52.2**
Turkmenistan	**58.1**	**1.4**	**59.4**
Uganda	4.1	10.6	14.8
Ukraine	39.6	7.3	46.9
United Arab Emirates	28.4	0.4	28.8
United Kingdom	25.9	4.8	30.7
United States of America	19.4	2.4	21.8
Uruguay	29.2	2.4	31.6
Uzbekistan	**57.5**	**1.9**	**59.4**
Vanuatu	27.1	14.9	42.0
Venezuela	25.3	2.2	27.5
Viet Nam	**56.0**	**0.7**	**56.7**
Yemen	**50.8**	**0.5**	**51.3**
Zambia	9.0	4.6	13.6
Zimbabwe	10.4	1.0	11.3
Worldwide	36.7	2.9	39.6

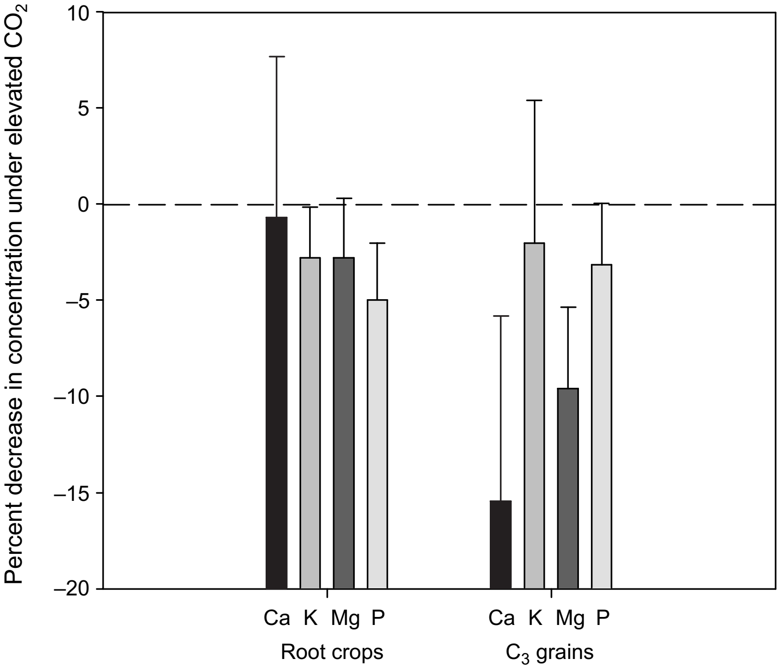

Figure 5 Effect of growth under elevated CO_2 on crop mineral concentrations. Means and 95% confidence intervals. Data taken from studies that measured all four minerals in the same tissues. For root crops, $n = 14$, for C_3 grains, $n = 16$. D.R. Taub and X. Wang, previously unpublished analysis.

elements, including calcium, iron, zinc, magnesium, and manganese, with a smaller decrease for phosphorous. In our own synthesis, there appears to be a general decrease in concentrations of the macronutrient mineral elements (those found in relatively high concentrations in plant tissues), particularly for C_3 grains, but also for root crops, although of a smaller magnitude (Figure 5).

The may be opportunities for mitigation of decreasing crop nutrient concentrations through adjustment of agricultural practices. Idso and Idso (2001) proposed that decreases in crop protein concentrations could be diminished or eliminated through increased use of nitrogen fertilizers. Supporting this, Taub et al. (2008) found that wheat protein concentrations were decreased by elevated CO_2 less under condition of high nitrogen supply (although protein concentrations still did decrease significantly). Adoption of this strategy would of course be difficult or impossible for those farmers with limited access to chemical fertilizers (UN Millennium Project 2005), and populations dependent on food supplied by such farmers may therefore remain particularly vulnerable to decreasing protein content as atmospheric concentrations of carbon dioxide continue to increase.

4.04.3.2.3 Effects of Past Increases in Atmospheric CO_2 on Food Quality

Although we are focused on potential effects of future increases in atmospheric CO_2, it is worth noting that the protein and mineral contents of crops may have already been affected by recent increases in CO_2. Experiments have found lower concentrations of protein in wheat flour from plants grown at current atmospheric CO_2 concentrations than in those grown at the concentrations found prior to the industrial revolution (Rogers et al. 1998; Ziska et al. 2004). Decreasing concentrations of protein have also been reported for wheat harvested in New South Wales, Australia between 1968 and 1990 (Conroy and Hocking 1993) and for a variety of garden crops in the United States from 1950–99 (Davis et al. 2004). Davis et al. (2004) also found decreases of 10–15% over the same time period for Ca, P, and Fe in food crops. Both Conroy and Hocking (1993) and Davis et al. (2004) suggested that changes in the cultivars used in agriculture likely accounted for much of the observed decreases in protein and mineral concentrations, but that increased atmospheric concentrations of CO_2 may also have contributed.

4.04.3.3.4 Effects of Elevated CO_2 on Forage Quality

In addition to decreasing nutrient concentrations in human food crops, increased atmospheric concentrations of CO_2 are likely to decrease protein and mineral concentrations in livestock forage species. For proteins, experiments show decreases in protein concentrations not only for forage grass species, but somewhat surprisingly, even for legume forages (Figure 6). Although there are less data available for minerals (other than N) than for protein, decreased concentrations of such minerals as phosphorus, potassium, and magnesium have been seen in both C_3 and C_4 forage species (Morgan et al. 1994; Newbery et al. 1995; Overdieck 1993; Owensby et al. 1993; Schenk et al. 1997).

The overall effect of elevated CO_2 on forage quality in mixed-species forage will be affected not only by changes in the nutrient content of each plant species, but by any changes that may occur in the species composition of the plant community (see Section 4.04.2.3.3). For example, Polley et al. (2011) in a tall grass prairie observed some decreases in mineral concentrations

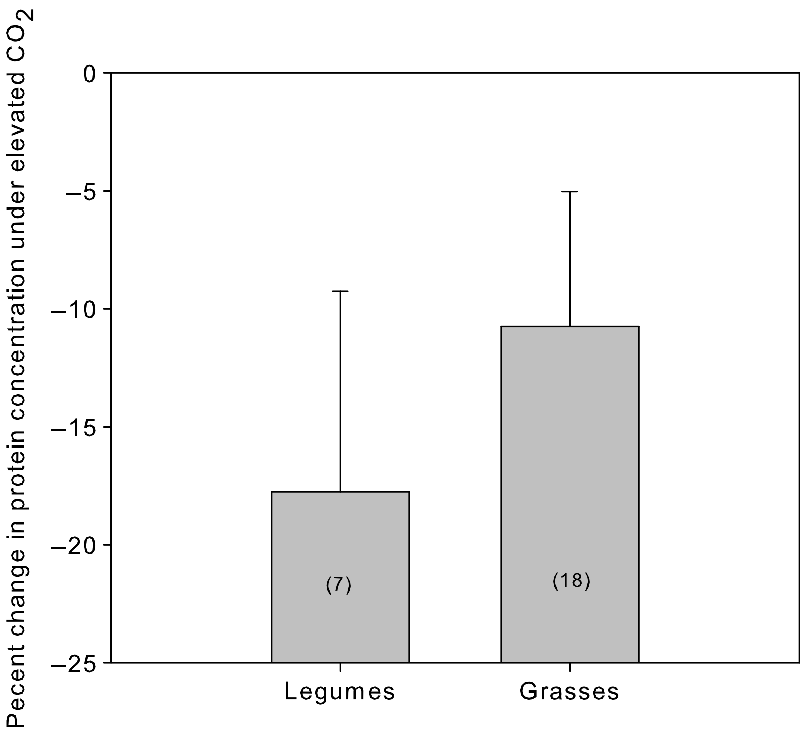

Figure 6 Effect of growth under elevated CO_2 on protein concentrations in legume and grass forage. Means and 95% confidence intervals. Number of experimental observations in parentheses. D.R. Taub and X. Wang, previously unpublished analysis.

(particularly phosphorus) of individual plant species under elevated CO_2. However, this was accompanied by shifts in the plant community toward species with a higher mineral content. The overall effect was therefore an increase in the average mineral concentration of the total available forage. This effect is likely specific to this plant community; in other communities, elevated CO_2 might instead favor plant species with a relatively low mineral content. In this case, changes in the plant community would exacerbate rather than ameliorate the decreases in forage mineral concentrations for individual plant species. On balance, because most forage species can be expected to experience decreased protein and mineral concentrations under elevated CO_2, nutrient concentrations in forage will likely decline, with potentially negative effects on livestock health and growth.

4.04.3.3 Impact on Undesirable Species

Weeds are undoubtedly the most prominent group of undesirable plant species because they infest a large number of agricultural crops in all regions of the world and cause serious economic damage (Figure 7). Because weed species have contrasting morphology, physiology, and life histories, these species will likely vary in their degree of response to CO_2 enrichment and other global environmental changes, which will occur nonuniformly in different parts of the world. Many weeds will increase their distribution and seriousness, whereas others may decrease in importance as a threat to agricultural ecosystems.

One analysis of the world's most noxious weed species found that the six most serious weeds and 9 of the 12 most serious weeds use the C_4 photosynthetic pathway (Holm et al. 1991; Wang and Mohan 2008), probably because the world's agriculture is mostly concentrated in warmer regions, where C_4 species have a competitive advantage over C_3 species. On one hand, higher temperatures resulting from increased atmospheric CO_2 may help these warmer-climate weeds expand toward higher latitude and greatly increase their geographic distribution (Patterson 1995). On the other hand, C_3 plants are generally more responsive in photosynthesis and growth to CO_2 enrichment than C_4 plants (see Section 2.03.1 Introduction). The outcome of the competition between C_3 and C_4 species will therefore be determined by the interaction of a number of factors in addition to CO_2 enrichment.

Another factor that will likely interact with CO_2 enrichment in the atmosphere in affecting undesired plant species is the shift in human populations around the world. Changes in the geographic distribution of humans will cause change in the use of particular crops in agriculture. As a result, the occurrence and seriousness of weeds will change because weeds are usually a problem specific to a certain crop species (Wang and Mohan 2008).

Although the precise effects of increased atmospheric CO_2 on particular weed species are difficult to predict, it is of ecological and economic significance to improve our understanding of the effects of CO_2 enrichment and other environmental changes on weeds and their interactions with crops (Wang and Mohan 2008).

One example of a geographically wide-spread weed species whose response to elevated CO_2 has been carefully studied is the common dandelion (*Taraxacum officinale*). Dandelion plants grown at elevated CO_2, produce a larger number of fruits per plant (Figure 8). Under elevated CO_2, their fruits also show morphological characteristics that favor increased enhanced

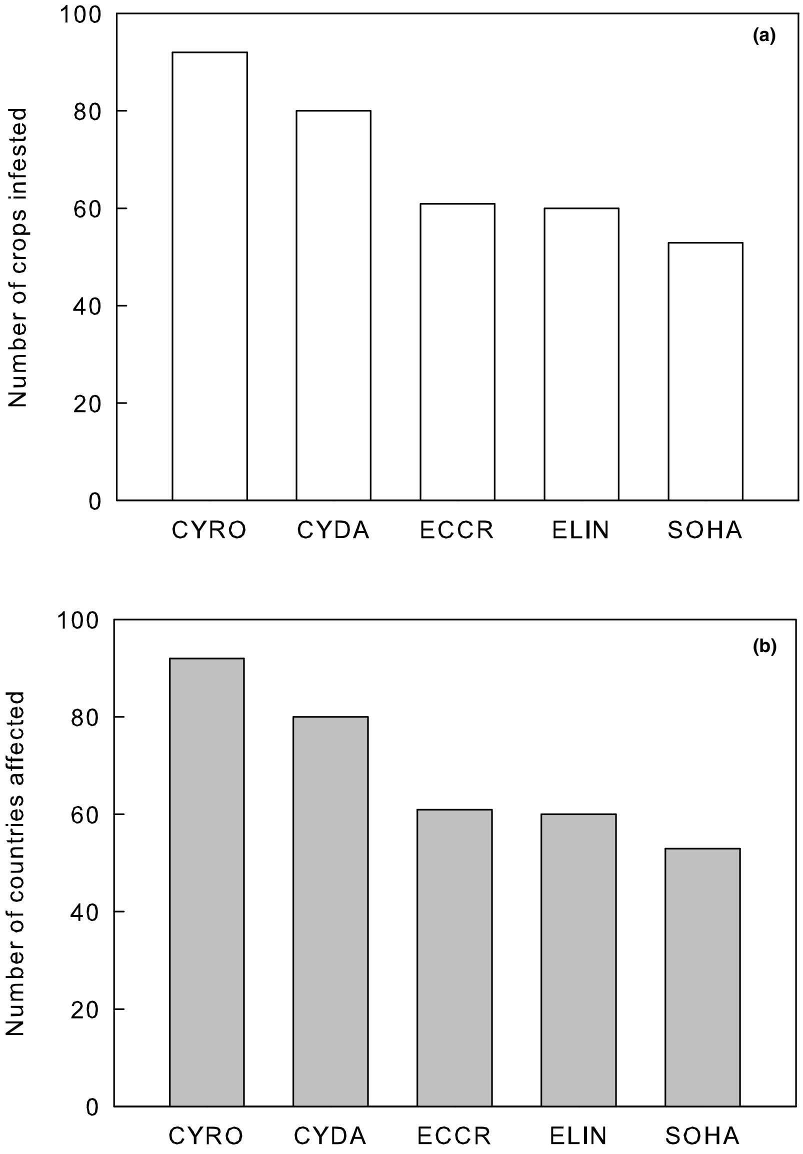

Figure 7 Seriousness of major weeds in terms of crops infested and the number of countries that reported the species as a major weed. CYRO, *Cyperus rotundus* (purple nutsedge); CYDA, *Cynodon dactylon* (bermudagrass); ECCR, *Echinochloa crus-galli* (barnyardgrass); ELIN, *Eleusine indica* (goosegrass); SOHA, *Sorghum halepense* (johnsongrass). Seriousness of weeds was extracted from Holm, L. G., D. L. Plucknett, J. V. Pancho, and J. P. Herberger, 1991: *The World's Worst Weeds: Distribution and Biology*. Krieger Publishing Company, 609 pp.

potential for long-distance dispersal by wind. Their seeds are also larger and germinate more readily than those grown under current atmospheric concentrations of CO_2. All of these changes suggest the potential for increased spread and increased density of dandelion populations under elevated CO_2 (McPeek and Wang 2007). Dandelion also has a number of nonreproductive features such as a high growth rate and competitive ability, which are likely to increase its success as CO_2 concentrations increase.

Another undesirable plant species that appears to receive a large boost from increasing atmospheric CO_2 is poison ivy, *Toxicodendron radicans*. Both FACE and growth chamber studies have shown growth stimulation by elevated CO_2 to be greater than for C_3 species in general (Mohan et al. 2006; Ziska et al. 2007). A shift under elevated CO_2 toward increasing production of the most virulent forms of the irritating agent urushiol has also been observed (Mohan et al. 2006). As with dandelion, poison ivy therefore appears to have the potential to become even more widespread and noxious in an enriched CO_2 world (McPeek and Wang 2007; Ziska et al 2007).

4.04.4 Summary

Increasing concentrations of atmospheric CO_2 over the next decades can be expected to have important implications for plant physiology and growth. Many plant species are likely to exhibit higher rates of photosynthesis and growth, decreased

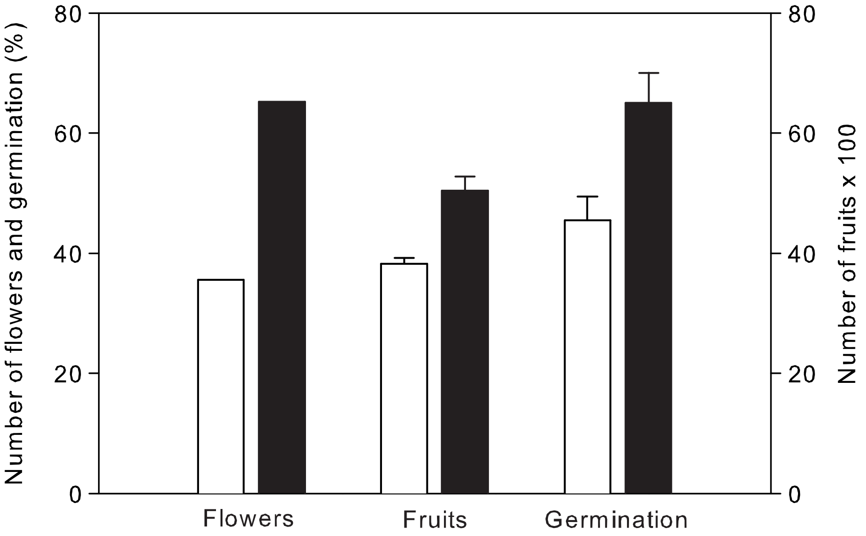

Figure 8 Number of flowers per plant, number of fruits per plant and germination percentage of fruits in dandelion plants grown at ambient (unfilled bars) and elevated (filled bars) CO_2. Data were extracted from McPeek, T. M., and X. Z. Wang, 2007: Reproduction of dandelion (*Taraxacum officinale*) in a higher CO_2 environment. *Weed Sci.*, **55,** 334–340 and re-analyzed.

water consumption and changes in tissue chemistry, including increased concentrations of nonstructural carbohydrates, and decreased concentrations of protein and minerals. These effects of increasing atmospheric CO_2 are not expected to be uniform among plant species. In particular, the physiological characteristics of legumes and plants that utilize the C_4 variant of photosynthesis suggest that these types of plants will show responses distinct from those of other species. The most likely threats to ecosystem services as a result of increased atmospheric CO_2 are (1) decreased crop and forage food values caused by decreased concentrations of proteins and minerals and (2) undesirable changes in plant community composition, including increases in populations of some major weed species.

See also: Advances, Vulnerabilities, and Opportunities for Corn: A Perspective from Iowa; Soybean; Climate Impact Analysis and Adaptations for Sustainable Rice Production System; Energy Resources and Policy: Vulnerability of Energy Resources and Resource Availability – Fossil Fuels (Oil, Coal, Natural Gas, Oil Shale).

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Relevant Websites

Brookhaven National Laboratory (USA) FACE, Information on FACE site technology and use. [Available online at http://www.bnl.gov/face/.]

Carbon Dioxide Information and Analysis Center, U.S. Department of Energy site providing an extensive repository of data and reports on global biogeochemistry. [Available online at http://cdiac.ornl.gov/.]

U.S. National Oceanic and Atmospheric Administration website with extensive data and graphics on atmospheric chemistry. [Available online at http://www.esrl.noaa.gov/gmd/ccgg/index.html.]

4.05 Invasive Plants and Animal Species: Threats to Ecosystem Services

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4.05.1 Introduction

The ongoing global redistribution of species is one type of environmental change that we are experiencing. Climate, eutrophication, ocean acidification, and land use change are other types of change that are occurring. None of these changes are occurring in isolation. They all are interacting to produce a myriad of changes, including local, regional, and global changes in flora and fauna (Davis 2009; Perrings et al. 2010; Pereira et al. 2010). Ultimately, this means that the effects of different drivers of environmental change cannot be studied in isolation. They must be studied using an integrated approach (Walther et al. 2009). This approach can challenge or redefine traditional paradigms that may have developed when the drivers were studied separately.

For example, climate effects may blur the boundaries between native and non-native species (Thomas and Ohlemüller 2010). Some species could enter a new region with human assistance while others could enter via natural migration due to altered weather patterns. Both will be new species to the area and both could cause problems. Moreover, a native species that may not have caused problems in a region could become invasive. A good current example of this is the explosive spread by the native mountain pine beetle and the enormous amount of tree mortality it is currently causing in areas of the Rocky Mountains, where it was not found before (Robins 2008). Conversely, a prior native invasive species may become less of a problem. Esper et al. (2007) documented 123 outbreaks of the larch budmoth in Southern Switzerland during the period 832–2004 C.E., with a mean period between outbreaks of 9.3 years, with never a gap between outbreaks of more than two decades. Between 1981 and 2007, not a single outbreak was recorded and the authors hypothesized that increasing air temperatures in this region during this period may be at least partly responsible for the absence of outbreaks.

Non-native species, like native species can be beneficial, harmful, or negligible in their effects. When a non-native species causes harm of some sort, it is typically described as invasive. Thus, the term ‘invasive species’ normally refers to non-native species that are producing consequences that humans do not like and deem harmful. The harm caused by non-native species is usually described as one of three types: threats to human health, economic harm, and ecological harm. Of the three, most people would likely agree that organisms that threaten human health, primarily introduced pathogens that are the causes of emerging diseases throughout the world, should be our first priority, followed probably by species that cause or threaten to cause great economic harm. One type of economic harm is the damaging or compromising of ecosystem services. Since the replacement of ecosystem services exacts an economic cost for a society, harm to ecosystem services is considered a type of economic harm in this chapter. Ecological harm would consist of ecological effects that do not have an economic cost, or threaten human health, but may still be deemed undesirable. Also, some species may cause more than one type of harm, and/or the type of harm might change over time. For example a species causing just ecological harm at the outset may begin to produce economic harm as time proceeds.

Among invasive species, introduced pathogens almost certainly pose the greatest threats to human well being and that of other organisms, having shown over and over their ability to devastate crops (e.g., 19th century potato blight in Ireland), livestock (e.g., rinderpest outbreaks in Africa in the 19th and 20th century), humans (e.g., 1918 influenza pandemic), and other plant and animal species (e.g., ongoing chytrid fungus epidemic killing frogs worldwide). However, introduced plants and animals also can cause great economic harm, often by damaging ecosystem services. In this chapter, I review some of the harm done to ecosystem services by non-native invasive plants and animals, as well as threats of future harm, and how climate is mediating these effects, sometimes exacerbating them and sometimes mitigating them.

There are dozens of types of ecosystem services, but they are commonly grouped into four categories: provisioning, regulatory, supporting, and cultural (MA 2005). Examples of provisioning services provided by nature are food, timber, fiber, and

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water. Regulating services include pollination, flood control, water purification, and processes reducing threats of disease and harm from climate. Tourism, recreation, aesthetics, and spirituality constitute cultural services, while supporting services include processes such as nutrient cycling and soil formation, which support the other services (MA 2005). The impacts of invasive plants and animals on these ecosystem services, as well as examples of how climate sometimes interacts with species introductions to produce these effects, are described separately in the following sections.

4.05.2 Impacts of Invasive Species on Ecosystem Services

4.05.2.1 Provisioning Services

In several cases, introduced tree species have been found to reduce surface water availability, particularly when replacing native herbaceous species, due to increased water uptake and evapotranspiration. In parts of New Zealand uplands, native tussock grasslands help provide water supplies for humans living at lower elevations. Due to their morphology and physiology, the grasses are efficient at capturing water, whether rain, fog, or snow, and they exhibit low rates of transpiration. As a result, the grasses released 64–80% of the precipitation to surface waters that were then accessible to humans (Mark and Dickinson 2008). In 1980, *Pinus radiata* was introduced to provide a timber resource. Twenty five years later, surface runoff, which provides water resources for the local residents, had declined by 50% (Mark and Dickinson 2008). A similar phenomenon occurred in South Africa, where the encroachment of *Pinus*, *Eucalyptus*, and *Acacia* in native upland environments similarly reduced water yield (Van Wilgen et al. 2008). A global meta-analysis of water use by native and non-native invasive plants showed that while there was little difference in sap flow rates, at the ecosystem scale, invasive-dominated ecosystems were more likely to exhibit higher sap rates per unit ground area than native-dominated ecosystems (Cavaleri and Sack 2010). On the other hand, comparisons between evapotranspiration rates between ecosystems dominated by invasive versus native species found no consistent differences (Cavaleri and Sack 2010).

For many people in the world, fish is a primary part of their diet. Evidence has shown that the introduction of some non-native fish or other organisms influence the economic value of the native fish used for food by altering the age-dependent survival probabilities. If the non-native fish prefer the larger native fish, then selection favors smaller fish and earlier maturation in the prey population, a process known as ‘stunting’ (Lehtonen 2002), which then directly impacts this primary food resource for local people. The dramatic negative impact on the North American Great Lakes fisheries by the sea lamprey, *Petromyzon marinus*, is well known. During the 1940s and 1950s, populations of the native lake trout, white fish, and chub collapsed and with it the associated fishing industry. Prior to the introduction of the sea lamprey into lakes like Michigan and Superior, annual US and Canadian harvests of lake trout exceeded 15 million pounds. By the early 1960s, the total Great Lakes harvest had dropped to 300 000 pounds, with harvests in some of the lakes being virtually nil (Great Lakes Fisheries Commission 2000).

The introduction of the comb jelly (*Mnemiopsis leidyi*) into the Black Sea is estimated to have reduced the anchovy harvest by 10% between the mid-1980s and the early 1990s (Travis 1993). Impacts on local fish populations were among the highest concerns when zebra mussels, *Dreissena polymorpha*, were introduced into North America and began to spread. Clear impacts on fish have been recorded, but the impacts are not always consistent. Commonly, planktivores decline following the introduction of the mussels, which deplete plankton populations. Fish feeding on benthic resources often increase in numbers but, many fish are able to utilize both pelagic and benthic resources and are able to buffer the changes produced by the mussels (Higgins and Van der Zanden 2010). Data have shown that the size of the impact, and in some cases, even the direction of the impact, varies across ecosystems and fish species (Strayer 2009), making it impossible at this point to be able to make any clear predictions of impacts on fish populations in a lake when colonized by zebra mussels.

The South American plant, *Salvinia molesta*, is recognized as one of the most widespread invasive aquatic plant species in the world, (Room 1990). It is able to double in cover every 3–4 days and can quickly infest entire freshwater systems (Room and Thomas 1986). In a short time, *S. molesta* can threaten local water supplies, and by making waterways unnavigable, prevent access to fish, which constitute a primary part of the diet of local residents (Stone 2011). In Papua New Guinea, entire villages had to be abandoned. The residents moved once local waterways were infested with this species (Stone 2011). Similar harm has resulted from the introduction of water hyacinth, *Eichhornia crassipes*. In Lake Victoria, its introduction has been documented to reduce fish harvests, water supplies, and in general, obstruct navigation through the waterways (Kasulo 2000). Other invasive species have undermined local water quality. In Southeast Asia, the Golden Apple Snail, *Pomacea canaliculata*, has converted what were originally naturally water-purifying wetlands into algal-dominated systems (Carlsson et al. 2004). Introduced carp can have a similar effect, transforming mostly clear lakes and streams into turbid systems (Angeler et al. 2002).

The negative impacts on timber resources of introduced insects have been well documented. In some instances, evidence suggests that warming is exacerbating the negative effects of these forest insect pests by permitting additional generations (Gomi et al. 2007). The hemlock wooly adelgid, *Adelges tsugae*, has been a primary source of mortality for the eastern hemlock, *Tsuga canadensis*, in many eastern North American populations (McClure and Cheah 1999; Lovett et al. 2006). Other prominent invasive insects in North America which undermine timber resources and/or services such as shade and cooling in urban areas, include the Asian long-horned beetle (Haack et al. 1996; Becker 2000), the balsam woolly adelgid (Hain 1988), the gypsy moth (Davidson et al. 2001), and the emerald ash borer (McCullough and Katovich 2004). The Asian long-horned beetle is also a timber pest in Europe (Vilà et al. 2010). The emerald ash borer arrived in this author’s neighborhood in 2009, which represented its first documentation in the state of Minnesota. The state of Minnesota is estimated to have 900 million ash trees, many of them growing in forests, but many also planted abundantly in cities to replace elms which had died due to the Dutch elm disease during the 20th century. Current estimates of the damage expected from the emerald ash borer, including loss of timber and costs to remove trees from yards, parks, and city streets, range from the tens to the hundreds of millions of dollars for Minnesota alone, and the species has spread throughout the entire upper Midwest, meaning regional costs will be much higher.

Introduced earthworms in Great Lakes forests of North America are known to have dramatically altered the physical and biogeochemical properties of the soil and litter layer, to the detriment of many native herbs (Frelich et al. 2006). They are also believed to be responsible for some of the declines in tree seedling success (Hale et al. 2006), which means they may constitute a threat to timber resources as well. Of course major threats to timber resources also come from native species. The southern pine beetle, *Dendroctonus frontalis*, is considered the most destructive insect pest of pines in the southern US. Price et al. (1992) estimated that the species had caused $900 million of damage between 1960 and 1990. The mountain pine beetle, *Dendroctonus ponderosae*, may be killing more trees in North America at this time than any other species. Perhaps due to a warming climate, the species has spread northward into areas where it had not previously been found, or at least where it had never been a large problem, such as portions of British Columbia. This raises an interesting question: if a native North American species expands its range on its own, should it be considered a non-native species in its new range? For the ecosystems and species in the new range, it makes little difference how the species got there. There is no clear scientific answer to this question. Individuals will disagree as to whether such a species should be considered native or non-native, which illustrates the increasing ambiguity that is developing, as these different global change drivers interact with each other. Distinct categories that may have made sense when a driver is studied separately can begin to break down when studied in the context of another driver, for example, invasive species studied in the context of climate change.

Some non-native species compete for forage in pasturelands where they have been introduced, thereby reducing the productivity of domesticated grazers. Wilson (1995) estimated that foraging by rabbits in Australian pasturelands costs the country $600 million annually. That introduced insects and weeds cause billions of dollars of damage to crops each year throughout the world is well known and will not be further discussed here. While insects (and pathogens) and weeds are normally the primary threats to crops, in some cases other animals cause significant harm as well, some of which are introduced. For example, the coypu (*Myocastor coypus*) causes extensive crop damage in parts of Europe (Bertolino and Genovesi 2007).

4.05.2.2 Regulating Services

Pollination of many crop and orchard species is a large ecological service provided by insects. While many studies of the effects of introduced insects on plant pollination have not focused on food plants, the results indicate the clear possibility that pollination extent and efficiency could be compromised by introduced species (Traveset and Richardson 2006). This can happen in several ways. Introductions of new flower visitors may reduce the visitation rates by native species, which may be more effective pollinators (Gross and Mackay 1998; Hansen et al. 2002; Dohzono et al. 2008). Introduced predators may reduce the size of native pollinator populations (Kelly et al. 2007). Also, introduced plants could compete with the native plants for pollinators (Brown and Mitchell 2001). Of course, it must be acknowledged that a primary pollinator of many crop and orchard species is the honey bee, *Apis mellifera*, an introduced species itself. The influence of non-native plants on native pollinator populations is an interesting question and some of the answers have been surprising. In some instances, non-native plants have been found to support native pollinators by providing nectar and pollen that may have been declining in the environment, due to a decline in some of the native plant species, or due to various factors, for example, land use change and climate change (Hughes et al. 2006; Kenta et al. 2007). On the other hand, non-native plants may compete with native plants for pollinators resulting in the decline of reproductive success of some of the native species (Morales and Traveset 2009).

Impacts on the global carbon cycle, particularly processes that influence the effects of natural carbon sinks, represent another type of regulating service. Studies on North American prairies have shown that the introduction of new plant species can reduce the ability of the system to sequester carbon. In particular, studies showed that the grasslands stored less carbon when crested wheatgrass, *Agropyron cristatum*, was introduced and replaced many of the native grass species (Christian and Wilson 1999; Curtin et al. 2000). A similar finding was documented in Hawaii where the replacement of native forests with non-native grasslands resulted in a 93% reduction in above-ground biomass, and consequently a dramatic reduction in the above-ground carbon storage (Litton et al. 2006). On the other hand, Wardle et al. (2007) found that the introduction of invasive predators on islands promoted ecosystem carbon sequestration.

One of the most important threats to ecosystem services involves the harm to grazing animals by some introduced plants. Leafy spurge (Leistritz et al. 1993), yellow starthistle (Eagle et al. 2007), and knapweed (Ridenour and Callaway 2001) are estimated to cost landowners and ranchers well more than $100 million per year (Duncan et al. 2004; and Eagle et al. 2007). Some introduced vertebrates can also diminish the value of pastureland.

Invasive seaweeds are known to produce population, community, and ecosystem effects, although long-term studies are still mostly lacking (Williams and Smith 2007). For example, while the invasive seaweeds may increase primary productivity, it is not yet known whether this may lead to increased abundances of species that might be utilized as food by local human residents (Williams 2007). In some cases, the opposite is believed more likely. Eutrophication is a common consequence of invasive seaweeds, which can trigger algal blooms, which in turn can compromise the productivity of other organisms that humans may use for food (Williams 2007). Introductions of other marine organisms have also been documented to undermine ecosystems services, including decline in food production and decline in property values (Williams and Grosholz 2008). Introductions into freshwater systems can have similar diverse consequences, from affecting particular species to affecting ecosystem processes (Ricciardi and MacIsaac 2011). These impacts include effects on nutrient cycling and primary productivity and significant alteration of the habitat (Ricciardi and MacIsaac 2011). In one instance, the introduction of a non-native planktivorous fish resulted in three native planktivores to shift their diets from zooplankton to benthic organisms near shore. This resulted in an increase in mercury concentrations in all three species (Eagles-Smith et al. 2008). As is the case in estuarine and marine systems, introductions of non-native freshwater plants can significantly affect ecosystem services, including altering water quality (Rommens et al. 2003)

There is considerable evidence that emergent diseases have several root causes, including the direct transporting of pathogens from one region to another, habitat loss or human movement into wild habitats (both of which can increase the contact of humans with novel pathogens), and the decline in biodiversity (Pongsiri et al. 2009), which sometimes can be caused by invasive species. Biodiversity decline can contribute to the spread of disease by the loss of predators of common animal hosts for the disease, as well as dramatic declines in the numbers of animal hosts. (Pongsiri et al. 2009). The previous sentence may appear self-contradictory, but if too many animal hosts are infected than the frequency of human contact with the pathogen will increase. On the other hand, if the number of typical animal host declines too much, then the pathogens need to adopt alternative hosts, for example, humans. Some introduced animals can increase the threat of human disease by creating more breeding sites for the hosts of the pathogens. For example, through their rooting foraging behavior, feral pigs in Hawaii create depressions that can fill with water, thereby providing breeding sites for disease-carrying mosquitoes (Atkinson 1995). Similarly, the tsetse fly (*Glossina* spp.) has been found to utilize stands of an invasive tree, *Lantana camara*, as a new habitat (Leak 1999).

Some introduced species threaten flood control or erosion efforts. The great shipworm (*Teredo navalis*) has damaged dikes and other flood protection installments around the Baltic and North Seas (Leppäkoski et al. 2002). In Europe, the coypu increases erosion along rivers through its herbivory and burrowing into the banks (Bertolino and Genovesi 2007). Other non-native species have increased erosion, including introduced vertebrates on some islands (North et al. 1994) and the replacement of native plant species by non-native plants, the latter which proved to be less effective in erosion control (Lacey et al. 1989). Many invasive plant species have altered fire regimes, some of which can come with very high economic costs. It is estimated that the increase in fire frequency in the Everglades and Australia due to the introduction of a non-native tree, *Melaleuca quinqeunervia*, will cost hundreds of millions of dollars (Serbesoff-King 2003).

4.05.2.3 Supporting Services

In the Great Lakes region of the US, non-native earthworms are believed to be affecting such fundamental ecosystem processes such as soil organic matter decomposition, carbon cycling, and nutrient cycling (Hendrix et al. 2008). Interestingly, a model of the earthworm effects on primary productivity suggested that the earthworm presence may increase primary productivity through the conservation of nutrients in the ecosystem (Barot et al. 2007). Considerable data exist showing how species traits can substantially affect various ecosystem processes in freshwater systems, including nutrient cycling, levels of dissolve oxygen, and water clarity (Vaughn 2010). This indicates that introductions of new species have the possibility of significantly altering some of these processes. One of the best examples of introduced species altering ecosystem processes involves the introduction of non-native mussels into North American freshwater systems. For example, introductions of zebra mussels, *Dreissena polymorpha*, usually cause dramatic declines in phytoplankton and small zooplankton, which substantially increase water clarity, as well as levels of soluble nitrogen and phosphorus, which in turn have sometimes resulted in significant increases in the growth and abundance of macrophytes (Caraco et al. 1997, 2000).

On islands, major sources of nutrient inputs come from seabirds during the breeding season, when they transport nutrients acquired from ocean food to the islands via their feces. A number of recent studies have shown that the introduction of non-native predators, such as foxes and rats, can dramatically reduce the transfer of nutrients from the ocean to the island, thereby significantly affecting soil fertility, which in turn influences the type of vegetation that dominates (Fukami et al. 2006; Wardle et al. 2007). Wardle et al. (2009) showed that the introduction of the predators and the consequent disruption of the nutrient transfer between ecosystems reduced leaf nitrogen levels and reduced the rate of litter decomposition.

4.05.2.4 Cultural Services

Non-native plants have always been popular among gardeners who enjoy the added diversity and aesthetics that they provide to the environment. Warming climates are already providing opportunities for many popular plant cultivars to be planted further north. In Europe, some garden species are being successfully planted and maintained as far as 1000 km north of their recently historical range (Van der Veken et al. 2008). At the same time, other non-native species may threaten other cultural services. Examples include non-native plants infesting waterways and interfering with boat traffic and tourism (Eiswerth et al. 2005). Impacts by some aquatic invasive species that reduce desired fish populations or impede boat travel or otherwise interfere with tourist activities will significantly reduce the public enjoyment of these environments, not to mention the economic losses experienced by communities for which tourism was a primary industry. Of course what is deemed environmental harm by one person may be deemed a cultural service by another. For example, while the Minnesota European environmentalists and nature lovers were decrying the introduction and spread of garlic mustard (*Alliaria petiolata*) into Minnesota forests, the local Hmong population was out harvesting the species as a food source, thereby retaining their cultural practice of harvesting wild plants for food.

4.05.3 Looking Ahead: Climate and Its Effects on Invasive Plants and Animals

Depending on the species, climate facilitates or inhibits the spreading of some invasive species (Bradley et al. 2010, Diez et al. 2012). Regional changes in precipitation and temperature regimes can cause expansions, contractions, or shifts in species' ranges depending on the direction of the changes in temperature and precipitation and on how the individual species respond to these changes. It is likely that the spread of certain types of species would be more likely to be more sensitive to any alterations in regional and local climate change and that certain types of environments may be particularly vulnerable to species introductions influenced by climate.

4.05.3.1 Species Sensitive to Enhanced Spread

The likelihood that a species will spread into and establish in a new area is a function of how many propagules are introduced into the new area and the likelihood of establishment by individual propagules (Leung et al. 2004), the latter of which is due to how well the traits of the species match up with the ecological conditions in the new environment (Davis 2009). The nature of the altered conditions in the new environment due to climate will open the door to some species more than others. For example, if precipitation in an area increases, this may make new resources available to plants, not only water, but also possibly nutrients, the uptake of which may have been water limited in the past. Plant species adapted to take advantage of high resource conditions will be favored in these environments, assuming the species are able to disperse, or be transported, into them. In both plants and animals, non-native species that either have great natural dispersal abilities or are regularly transported by humans in one way or another would be able to best keep pace with any alterations geographically in weather patterns.

4.05.3.2 Particularly Vulnerable Environments

Some regions of the world are more vulnerable to species introductions if weather patterns change. These include high altitude environments and high latitude regions. High altitude environments provide several important ecosystem services including water supplies and recreational opportunities (Körner 2004). To date, many high altitude sites have yet to experience high rates of species introductions, probably due to a combination of low levels of propagule pressure and habitat disturbance, both a result of low amounts of human activity in these environments. However, more than one thousand species of non-native plants have established in high altitude sites throughout the world and while local species richness may increase at some sites, there is growing concern that some of these plants may negatively affect the highly valued ecosystem services provided by these environments (Pauchard et al. 2009). For example, the replacement of herbaceous or shrub vegetation by trees might result in increased evapotranspiration and less water export down to lower elevations (Mark and Dickinson 2008). Moderating temperatures would inevitably make it easier for many non-native species to spread into higher altitude sites. Also, the spread of non-native plants is likely increasing due to the increased connectivity between high altitude sites, which is resulting from increased movements by humans between sites, often facilitated by the construction of roads and/or recreation areas. The establishment of some non-native plants at these higher elevations may also be facilitated by atmospheric nitrogen deposition (Price 2006), bringing in yet another environmental change driver to interact with invasive species and climate.

Arctic regions have been reported to have experienced dramatic temperature increases over the past few decades, exceeding recent historical trends by 1.4 °C (Kaufman et al. 2009), although other data questions the magnitude of this increase [Alexeev et al 2012]. If surface temperature increases over the Arctic, which then warm the soils, and melt the permafrost, snow and ice, this would transform the terrestrial and marine arctic environments and making them amenable to more species. For example, it is estimated that 219 shallow water mollusk species in the northern Bering Sea have the potential to spread into the North Atlantic due to warming arctic waters without any human assistance (Vermeij and Roopnarine 2008). Increase shrub growth has been documented (Sturm et al. 2001) and the spread of other plants northward, some facilitated by humans and some not, is assumed. Like plants everywhere, they will alter ecosystem processes such as nutrient cycling and carbon sequestration. Some of the changes we may view as enhancing ecosystem services; some we may not. Antarctica currently has only two native vascular plants, Antarctic hairgrass, *Deschampsia antarctica*, and Antarctic pearlwort, *Colobanthus quitensis* (Caryophyllaceae). If surface temperatures warmed and increasing human travel to Antarctica by scientists and tourists, new plant species, as well as animal species, would be arriving soon, if they have not done so already. The number of species in high latitude regions would almost certainly increase since the number of introductions will likely exceed the number of extinctions, perhaps substantially. It is also expected that hybridization will be common between some of the new and long-term residents (Vermeij and Roopnarine 2008).

Environments experiencing increased resource availability are particularly vulnerable to the establishment of new species (Davis et al. 2000). As described above, if climate permits increased water and/or nutrient availability in an environment, it would be more invasible to many plant species. Similarly, if the local and regional climate results in an increase in primary productivity, the increase of food availability would likely make the habitat more invasible for herbivores.

4.05.3.3 Environments Not Likely to Be Vulnerable to the Introduction of Invasive Species

No environment is immune to the introduction of new species. Evidence has shown that all environments are invasible to some extent (Davis 2009). While climate effects may change the invasibility of certain environments with respect to some species, all terrestrial, freshwater, and marine coastal environments would experience species introductions in the future. However, there is one group of environments that probably would be less affected by the interaction of species introductions and any long-term alterations in weather patterns than others. This is not because these environments are less invasible, but rather because they are already occupied mostly by non-native species. These are areas where human disturbance has been high for a long time, such as urban areas and agricultural lands. Undoubtedly, there would be some exchange of species due to climate, with some non-native species being replaced by other non-native species. However, these environments would not experience dramatic shifts in the relative abundance of long-term residents and newly arrived species, as would be the case in many forests, grasslands, wetlands, rivers and lakes, and coastal marine systems, which have currently experienced less intense human disturbance—hence typically are inhabited by proportionately fewer non-native species than are the highly anthropogenically disturbed environments.

4.05.3.4 Challenges in Distinguishing Harm from Change

There is an emerging consensus that invasive species and climate can no longer be studied as independent drivers (Davis 2009; Walther et al. 2009; Thomas and Ohlemüller 2010). Climate influences which species are able to live in particular areas and also what their ecological effects are. Native species that historically may have been beneficial, or at worst a periodic annoyance, could become invasive and very harmful, as is happening with the mountain pine beetle in North America. Some native species that may have been providing important ecosystem services may decline in numbers or even disappear from a region if weather patterns change. In this case, some non-native species may prove to be highly desirable if they are able to replace those ecosystem services and efforts may be undertaken to increase and facilitate their establishment (Walther et al. 2009). As emphasized by Thomas and Ohlemüller (2010), the traditional perspective that native species are 'good' and alien species are 'bad,' which dominated conservation and alien control programs is no longer viable.

The mere characterization of species as native and non-native is believed by many to becoming a dubious exercise, which will only increase in dubiousness as the years go by (Davis 2009; Thomas and Ohlemüller 2010; Davis et al. 2011), particularly since any alteration in weather patterns could shift the ranges of species resulting in new mixtures of species. Pejchar and Mooney (2009) emphasized that many invasive species have turned out to have positive impacts for local residents, and urged caution in making quick and knee-jerk assumptions about the effects of introduced species. Ultimately, determining harm is not a scientific decision, even if scientists are the ones making the decision. This represents a social decision, and one in which different stakeholders may honorably disagree. For example, herbalists may view introduced plants as promising new medicinal value and urban landscape architects may view non-native plants as being able to provide valuable ecosystem services to urban environments (del Tredici 2010). This important fact is recognized by the National Invasive Species Council in the US: 'Some non-native species are considered harmful, and therefore, invasive by some sectors of our society while others consider them beneficial. This discontinuity is reflective of the different value systems operating in our free society, and contributes to the complexity of defining the term *invasive species*' (NISC 2006).

I do not believe we can proceed with definitions of negative impacts from invasive species similar to the following: 'Negative impacts documented included, for example, predation, competition, change in fire regimes, displacement of native species, and modification of succession processes' (MgGeoch et al. 2010). Under such broad definitions, any non-native species could be declared invasive. If almost any ecological impact is enough to consider a species invasive, then almost any non-native species could be considered a threat to ecosystem services, since it takes little imagination to connect some ecological change with some potential threat to an ecosystem service. As a society, we need to be discriminating. We need to be slow to characterize any species as invasive, since that essentially obligates society to spend resources to fix 'the problem.' We need to be sure not to confuse harm with change. We need to focus on those species, both native and non-native, that are truly causing harm or are threatening to cause harm, to ecosystem services. The same holds for climate. Depending on the location and its effects, alterations in long-term weather patterns by itself is not necessarily harmful, and in fact may be regarded as beneficial by people in some places due to its effects, for example, by increasing food production due to increased growing seasons and/or precipitation. Similarly, the changes resulting from the interaction of climate and species introductions should not automatically be considered harmful.

4.05.3.5 Managing Our Priorities

We should stop judging species on their origins and instead focus more on their effects (Davis et al. 2011). Like native species, some non-native produce desirable effects, some are mostly benign, and some, the ones we call invasive species, cause problems, sometimes severe problems. It is of the utmost importance that we distinguish between severe problems and smaller problems, or even question whether we are calling simple change a problem. Any new species will cause some ecological effect. It may affect nutrient cycling, it might compete with other species, it might be prey on other species, but it will always have effects. This means that as long as we study hard enough, we will be able to document ecological effects of every single non-native species. Clearly, society does not have the resources to fund claims amounting to little more than personal preferences. Society needs to retain its resources so that they can be used to manage and mitigate the significant harm to ecosystem services produced by some non-native species.

Given limited social resources, scientists, land managers, and policy makers owe it to the public, who are usually providing the funding, to seriously question whether or not action should be taken to eradicate or manage a non-native species or try to mitigate its effects. Specifically, the following seven questions should be asked.

1. Do the net effects on ecosystem services by this species truly constitute harm, or can the effects be regarded simply as change?
2. Can we learn to live with this species?
3. If we decide we must manage or control it in some way, does an effective management approach actually exist?
4. Does this management approach make sense in the context of the spectrum of climate effects on the environment now and what is possible in the future?
5. If an effective management approach does exist, are we confident that the benefits we will receive from the management intervention will exceed the costs (with costs including not only dollars, but other inevitable effects on the environment and other species, including ourselves)?
6. Are we sure we would not prefer to spend these resources on some other environmental project or initiative?
7. Are we confident we are not throwing money down the drain?

4.05.4 Conclusion

Ultimately, our decisions regarding what to do with invasive species become economic. Of the thousands of non-native species that have entered and will continue to enter our countries in the future, we will only have the resources to manage a small proportion of them. We need to make smart decisions, which means we need to begin using the term invasive more sparingly. Like it or not, these new species are not going back. No matter what we call them, they are our new residents, except in extremely rare cases when an all out eradication campaign is undertaken and is successful, for example, the eradication of a deadly human pathogen from a country. Clearly, when the damage, or threatened damage, by plants and animals to ecosystem services is very high and clearly outweighs the costs and harm associated with whatever management measures will be undertaken, society needs to invest its resources to try to control these.

Although it sometimes seems that non-native species are considered as a kind of toxic or nuclear waste (e.g., with threats of an invasional meltdowns), or some kind of demons that threaten life as we have known it, we are talking about species—plants and animals, our fellow inhabitants of planet earth. As described by Peter del Tredici (2010) in his book 'Wild Urban Plants of the Northeast,'

> The confluence of climate change and urbanization—acting in concert with the global spread of species—has set the stage for spontaneous vegetation to play a major ecological role in the human dominated landscape (Ziska et al. 2004; Christopher 2008; George et al. 2009). Regardless of how humans feel about this brave new ecology, the plants described in this book are well adapted to the world we have created, and as such, are neither good nor bad—they are us.

In the end, we really have little choice. Climate influences and species introductions will continue into the foreseeable future no matter what humans decide to do or not do. We will continue to devote considerable resources to try to protect our ecosystem services from threats from particularly harmful invasive species. However, in many instances, rather than trying to manage the endless introductions, we would do better to try to manage our attitudes toward them. Although we do have some ability to shape the direction and combined impacts of climate and species introductions, ultimately, like other species, we are going to have to adapt and accommodate these changes into our lives, economies, and cultures.

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4.06 Does Climate Change Increase the Risk of Disease? Analyzing Published Literature to Detect Climate–Disease Interactions

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Glossary

Bioclimatic model A model that integrates knowledge of physics, ecology, and physiology to predict how ecological systems will change in the future in response to environmental factors.

Climate change One definition used is that it is a significant and lasting change in the statistical distribution of weather patterns over periods ranging from decades to millions of years. In this chapter, we focus on the climate variables of temperature and precipitation. More generally, climate change refers to alterations in the climate system which is the system consisting of the atmosphere, hydrosphere, lithosphere, and biosphere, determining the Earth's climate as the result of mutual interactions and responses to external influences (forcing). Physical, chemical, and biological processes are involved in interactions among the components of the climate system (NRC 2005).

Infectious disease Illness resulting from the infection, presence, and growth of pathogenic biological agents in an individual host organism.

Macroparasite A parasite that grows in its host, but multiplies by producing infective stages that are released from the host to infect new hosts. They are often intercellular or live in body cavities, rather than within the host cells. Examples include ticks, mites, nematodes, and trematodes.

Microparasite A parasite that completes its life cycle within a single host and can be transmitted directly between hosts. They often reproduce within a host's cells and are generally too small to be seen with the naked eye. Examples include viruses, bacteria, and fungi.

Physiology The study of an organism's vital functions, including growth and development, the absorption and processing of nutrients, the synthesis and distribution of proteins, and other organic molecules, and the functioning of different tissues, organs, and other anatomic structures.

4.06.1 Introduction

Ongoing increases in human population density have led to increased agricultural expansion, pollution, introduction of exotic species, and overharvesting of resources. Two of the most pressing concerns currently confronting society are local impacts of climate and the emergence of infectious diseases. According to the Intergovernmental Panel on Climate Change (IPCC 2007), observed changes in climate patterns are due in part to the effects of anthropogenic activities. Documenting the consequence of these changes for species' distributions, phenologies, and biodiversity has become a major focus of biologists (Walther et al. 2002; Parmesan 2006; Parmesan et al. 2011; Parmesan and Yohe 2003). Growing evidence indicates

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that such effects would manifest across multiple scales of biological organization, ranging from individuals to ecosystems (Post et al. 2009; Hoegh-Guldberg and Bruno 2010; Woodward et al. 2010). Simultaneously, disease ecology has received increased attention due to the emergence of many new infectious diseases (Daszak et al. 2000; Woolhouse 2002; Jones et al. 2008). While the emergence of human diseases (e.g., HIV/AIDS, SARS, and malaria) has received the most attention, emerging diseases have also become a growing problem for plants, livestock, and wild animals (Daszak et al. 2000; Woolhouse 2002; Dobson and Foufopoulos 2001).

A key question is whether these two patterns are related. Owing to the well documented and often positive effects of temperature on pathogen replication, it has often been suggested that current and plausible increases in temperature would enhance transmission and/or exacerbate patterns of pathology (Martens et al. 1995; Bruno et al. 2007; Canto et al. 2009; Harvell et al. 2009). However, warming temperatures can also drive decreases in infections by increasing the mortality rate of pathogens or enhancing host immune function (Paull and Johnson 2011a,b; Studer et al. 2010). In a recent forum in the journal *Ecology*, eminent researchers in the field of disease ecology debated whether local and regional climate conditions could increase the prevalence of infectious diseases. Within this forum, researchers presented arguments along with accompanying data to support increases as well as decreases in the prevalence of particular infectious diseases. In coral, for instance, there appears to be clear evidence that warmer sea temperatures are linked to increased incidence of diseases (e.g., white syndrome, Caribbean yellow band disease (CYBD)), possibly through temperature-mediated suppression of the host immunity (Figure 1; Bruno et al. 2007; Harvell et al. 2009). However, associations between temperature and disease emergence can be obscured by a diversity of cofactors often associated with humans. For example, the spread of malaria into new regions could be curtailed by greater health care resources and active vector-control policies (Hay et al. 2002; Randolph 2009; Chaves and Koenraadt 2010).

Climate-driven changes in infectious disease would likely be a function of both physiological changes of hosts and parasites in response to climate, as well as alterations in the ecological interactions between hosts and parasites (Lafferty 2009). This observation emphasizes the importance of generating detailed knowledge about the specific hosts and pathogens involved in the interaction, how these species are affected by climate change individually and together, and how changes in community structure affect the host–pathogen interaction. These realizations have refocused current efforts toward determining what forms of local and regional climate conditions are likely to influence infection and for what types of diseases we might see increased infections with shifts in temperature or in other climate variables such as precipitation, cloudiness, etc. Importantly, these challenges are not unique to disease ecology, but inherent to research examining species interactions such as pollination, predation, and competition in the face of climate change (Gilman et al. 2010; Tylianakis et al. 2008). In the sections that follow, we provide an overview of the predicted and observed effects of climate change on host–parasite interactions, evaluate the available literature for evidence of climate effects on disease emergence, and discuss future directions that could help expand our understanding of climate-mediated effects on disease.

4.06.2 Challenges Inherent to Detecting a Climate-Driven Signal in Infectious Diseases

Understanding the effects of climate on patterns of disease is complicated by the fact that disease represents the product of interactions between at least two species – a host and a pathogen – each of which may respond differentially to elements of climate such as temperature, precipitation, and the variance associated with these variables. In part, these responses depend on the type of pathogen involved. Pathogens are often classified as microparasites (e.g., viruses, bacteria, fungi) or macroparasites (e.g., helminths, arthropods) that tend to cause disease in hosts under particular conditions. In some cases, other species such as vectors (e.g., mosquitoes, ticks) are also involved in transmission. Importantly, environmental cofactors can influence the progression from infection to disease (Patz et al. 2000). Climate influences the physiology and phenology of most species, resulting in altered species ranges or interactions, changes in host or pathogen abundance, and evolutionary processes if there are local and/or regional changes in climatic conditions (Parmesan 2006; Parmesan and Yohe 2003; Visser and Both 2005). By extension, these changes have been hypothesized to positively affect disease by increasing the pathogen replication rate and shifting species' distributions (Harvell et al. 2009; Ostfeld 2009). Here, we provide an overview of how climate can affect host–pathogen interactions based on theoretical studies as well as field and experiment-based research.

4.06.2.1 Physiology

The metabolic processes of organisms, including hosts, pathogens, and vectors, are intimately linked to variation in temperature. For example, owing to their smaller size, higher metabolism, and faster generation time, pathogen replication rates are expected to increase with temperature, which could positively affect disease dynamics (Rohr et al. 2011). Research across a range of systems supports the argument that higher temperatures tend to enhance pathogen growth (Harvell et al. 2009; Kutz et al. 2005). For example, Harvell et al. (2009) demonstrated a positive correlation between CYBD lesion growth on coral colonies and mean water temperatures. Increased temperatures have also increased the developmental rate of Arctic nematode larvae, a parasite of muskoxen, leading to the completion of development within one season rather than two (Kutz et al. 2005). Collectively, this research suggests that warming could enhance the abundance of certain parasites. However, simultaneous changes in growth and mortality rates in addition to variation in parasite virulence and host susceptibility with temperature make predicting the net effect of temperature on disease dynamics challenging. For example, studies of trematode parasites show that warmer temperatures increase the rates of parasite development, as well as mortality over the range of temperatures (Paull and Johnson 2011b; Studer et al. 2010). Climate-driven physiological changes in hosts and parasites can also impact parasite virulence and host susceptibility to infection (Bruno et al. 2007; Studer et al. 2010; Garrett et al. 2006; Møller 2010), which can lead to either opposing additive or synergistic effects on parasite abundance and host pathology. For instance, Rojas et al. (2005)

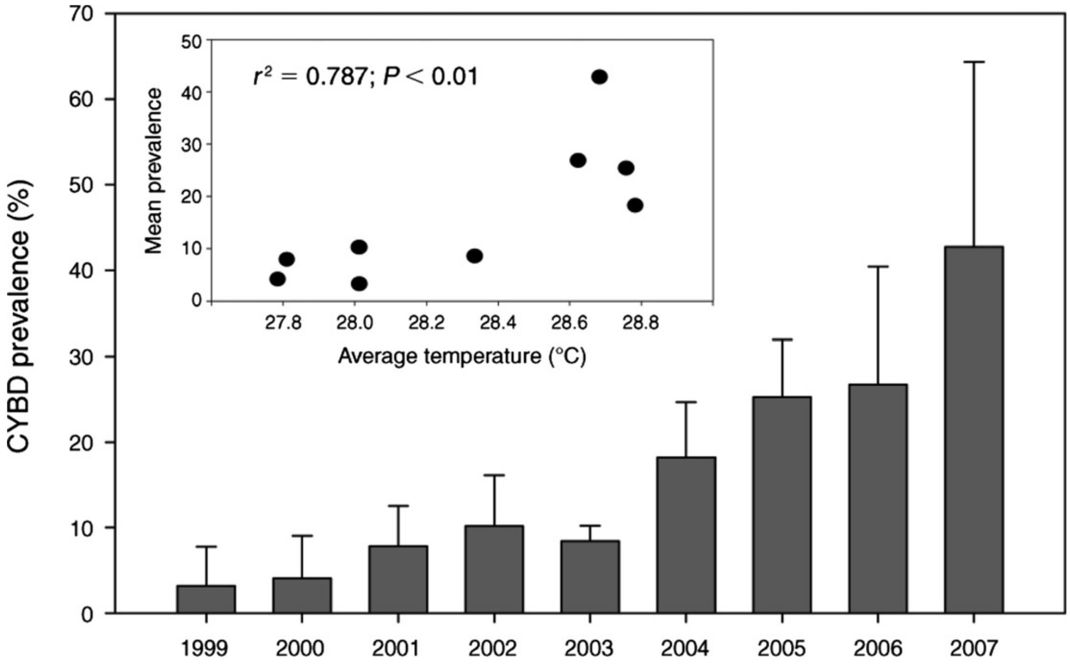

Figure 1 Temporal changes in Caribbean yellow band disease (CYBD). Increase in CYBD prevalence in the Caribbean coral genus *Montastraea* in reefs off the southwest coast of Puerto Rico from 1999 to 2007. The inset shows the positive and significant correlation between the yearly increase in mean prevalence and the average yearly surface water temperature. Harvell, D., S. Altizer, I. M. Cattadori, L. Harrington, and E. Weil, 2009: Climate change and wildlife diseases: When does the host matter the most? *Ecology*, **90**, 912–920. Reprinted with permission by the Ecological Society of America.

demonstrated that the amphibian pathogen *Ambystoma tigrinum* virus (ATV) replicates faster at 26 °C compared to 10 °C in cell culture, yet salamanders failed to develop lethal viral infections at 26 °C due to potentially enhanced immune function at higher temperatures.

4.06.2.2 Range Shifts and Extinctions

Changing temperature and precipitation patterns are leading to shifts in the ranges of hosts, vectors, and pathogens as climatic conditions approach the optima for numerous species (Ostfeld 2009; Purse et al. 2005; Pascual et al. 2009). The climate-mediated movement of pathogens into new regions containing naïve hosts has been a hypothesized mechanism of disease emergence (Ostfeld 2009; Pascual et al. 2009). Bioclimatic models, which use information on the current distribution of species in relation to the current climate to project future shifts in distribution according to the IPCC climate predictions, are frequently implemented to predict how pathogen ranges might shift or expand with plausible changes in local and regional climate (e.g., González et al. 2010). One theoretical argument for the hypothesis that the future climate could lead to range expansion of diseases is that temperature minima are predicted by the IPCC to increase more than the maxima, such that future temperatures may be more likely to increase into the range of temperatures tolerated by pathogens, rather than exceed this range (Ostfeld 2009). For instance, bluetongue virus, a pathogen of ruminants, has expanded its range into 12 European countries since 1998, as a result of milder winter temperatures that favor virus persistence and vector recruitment (Purse et al. 2005). Several bioclimatic models also have demonstrated that the range where climate conditions are suitable for the survival of a wide variety of pathogens and vectors may expand (Bergot et al. 2004; Ogden et al. 2008). However, while climate-driven increases in disease incidence have already been observed along elevational and latitudinal boundaries (Purse et al. 2005; Alonso et al. 2011), this is unlikely to be a universal pattern across all diseases (Lafferty 2009). For instance, several studies point to the possibility of reduced ranges (Randolph and Rogers 2000; Roedder et al. 2010). Such studies demonstrate that although climate affects the total area suitable for pathogen survival (the potential niche), factors such as dispersal limitations, interspecific interactions, and disease control efforts may prevent the pathogen from actually capitalizing on such potential range expansions (the realized niche) (Jeschke and Strayer 2008). Range contractions could also occur if hosts, pathogens, or vectors are dispersal limited, or if their local and regional climate disrupts the interspecific interactions required for disease transmission (Lafferty 2009; Randolph and Rogers 2000).

4.06.2.3 Species Interactions

The combination of climate effects on physiology, phenology, and species distribution ultimately affects species interactions within communities (Gilman et al. 2010). As can be expected, climate-mediated effects on species interactions vary tremendously depending on the system, the type of species interaction (e.g., mutualism, predation, herbivory, competition), and the type of environmental driver (e.g., land use change, nitrogen deposition, CO_2 enrichment, elevated temperature; 24). However, in a review of 688 published studies examining species interactions in the context of environmental change, Tylianakis et al. (2008) found some general patterns including (1) reduced interaction strength in plant–animal mutualisms, (2) changes in the competitive dominant in plant and animal communities, and (3) both positive and negative shifts in the frequency and abundance of predation and herbivory events. Hosts, parasites, and vectors can respond differently to climate, leading to possible shifts in the timing and consequences of host–parasite interactions (Paull and Johnson 2011a,b). For instance, milder winters could limit epidemic chytrid infections of the diatom *Asterionella formosa* by allowing parasites to infect *Asterionella* prior to (rather than during or after) the diatom bloom, effectively limiting population growth of both the host and the parasite [(Ibelings et al. 2011) for an example involving algal–grazer interactions see also Winder and Schindler (2004)]. Similarly, a long-term study of barn swallow parasites found that the 'relative capture date' of louse flies relative to adult barn swallows grew progressively earlier over the decades, suggesting that louse fly phenology changes are stronger than those of its swallow host (Møller 2010). Such changes in the timing of host–parasite interactions could have consequences for disease dynamics and host pathology, highlighting the importance of accounting for climate-driven changes to interspecific interactions when predicting future disease dynamics.

4.06.3 A Retrospective Literature Analysis of Climate Change and Disease

In light of the potential complexity surrounding host–parasite interaction outcomes in response to climate, a valuable tool for assessing the state of the research field and the observed empirical results is through an examination of published studies. Given that, in some regions, observations of climate have been recorded for at least the last half century (IPCC 2007), a retrospective evaluation of available research is long overdue. Recent literature reviews suggest that interest in the effects of climate on disease dynamics is increasing within the academic community (Rohr et al. 2011; Paull and Johnson 2011a,b). To date, however, the idea that contemporary changes in climate have led to broadly observed changes in infection patterns has not been empirically tested using published studies. If there is evidence for an increased focus on climate-mediated effects on disease dynamics, this raises an important question: Does the increase in studies on climate–disease interactions reflect a growing body of evidence linking shifts in climate to patterns of disease? While experiments have highlighted the potential mechanisms underlying climate-mediated effects on disease and theoretical studies have predicted disease dynamics in the face of changes in local and regional climatic conditions, whether the observed changes in climate over the past several decades have positively contributed to disease emergence remains largely conjectural. Few studies have synthesized the literature to assess the evidence for an association between climate and disease.

4.06.3.1 Assessing Interest in Climate–Disease Interactions

We used the literature survey methods of Ward and Lafferty (2004) to address whether the frequency of publications examining climate-driven effects on infectious diseases has increased over the past four decades after accounting for research effort (normalized by the total number of publications on climate) and for temporal autocorrelation (see Johnson and Paull 2011). We developed title-specific search strings using the literature search engine ISI Web of Science, which included separate terms related to either disease (see Johnson and Paull 2011) or climate change {TI=[climate* and (change or shift* or disrupt* or anomal* or variation or variability or warm*) or (global and warming) or [extreme and (event* or drought* or flood*)] or (el and nino) or (la and nina)]}. We identified 249 articles published between 1970 and 2010 that included climate and disease related search terms in the title and 9208 articles published between 1990 and 2010 that included these terms in the title or the abstract. Our retrospective evaluation indicated that, prior to 1990, very little research addressed the linkage between climate and disease emergence. In fact, no articles satisfied the joint search criteria used in this chapter during the period from 1970 to 1989 (e.g., none of the articles on climate change also included the disease search terms in the title). After 1990, however, both the total and the proportion of climate change research focused on disease have increased steadily and significantly (**Figure 2**). We used Generalized Additive Mixed Models (R package mcgv) to test for a significant effect of year, along with an information theoretic approach to evaluate the fit of different autoregressive moving average (ARMA) terms (p and q) across different lags to account for temporal autocorrelation (Johnson and Paull 2011). After accounting for the general increase in research (as indicated by the total number of publications on climate change), we observed an approximate doubling in publications over the past 20 years (from $<1\%$ in 1990 to $>2\%$ in 2010 for title-based searches). The same pattern was also observed using article abstracts for the period between 1990 and 2010, although the increase was generally linear (e.g., no smoothing term was needed). Thus, despite the complexity inherent to understanding climate-mediated effects on disease, these results suggest that interest in climate-mediated effects on disease has increased significantly and substantially over time.

4.06.3.2 Assessing Evidence That Climate Shifts Affect Patterns of Disease

We narrowed our literature search to long-term field studies (≥ 5 years) that examined the effects of climate on disease within wildlife populations. We opted to exclude human disease studies because several confounding variables such as socioeconomic factors and prevention strategies obscure our ability to assess climate–disease linkages, and several interesting reviews have addressed this topic in greater detail (Randolph 2002; Reiter 2001; Zell et al. 2008). We identified only 11 publications from over 477 possible articles (**Table 1**), and of these 11, 3 reported results from multiple pathogens or parasites. Thus, there were 17 total reports of climate-mediated effects on disease from the 11 studies. Across the 11 studies, there were 10 reports (59%) of increased pathogen or disease incidence with temperature increases and precipitation changes (**Table 1**). By contrast, there were three reports (18%) of decreased pathogen or disease incidence with temperature increases and precipitation changes and four reports (23%) of no change. While the

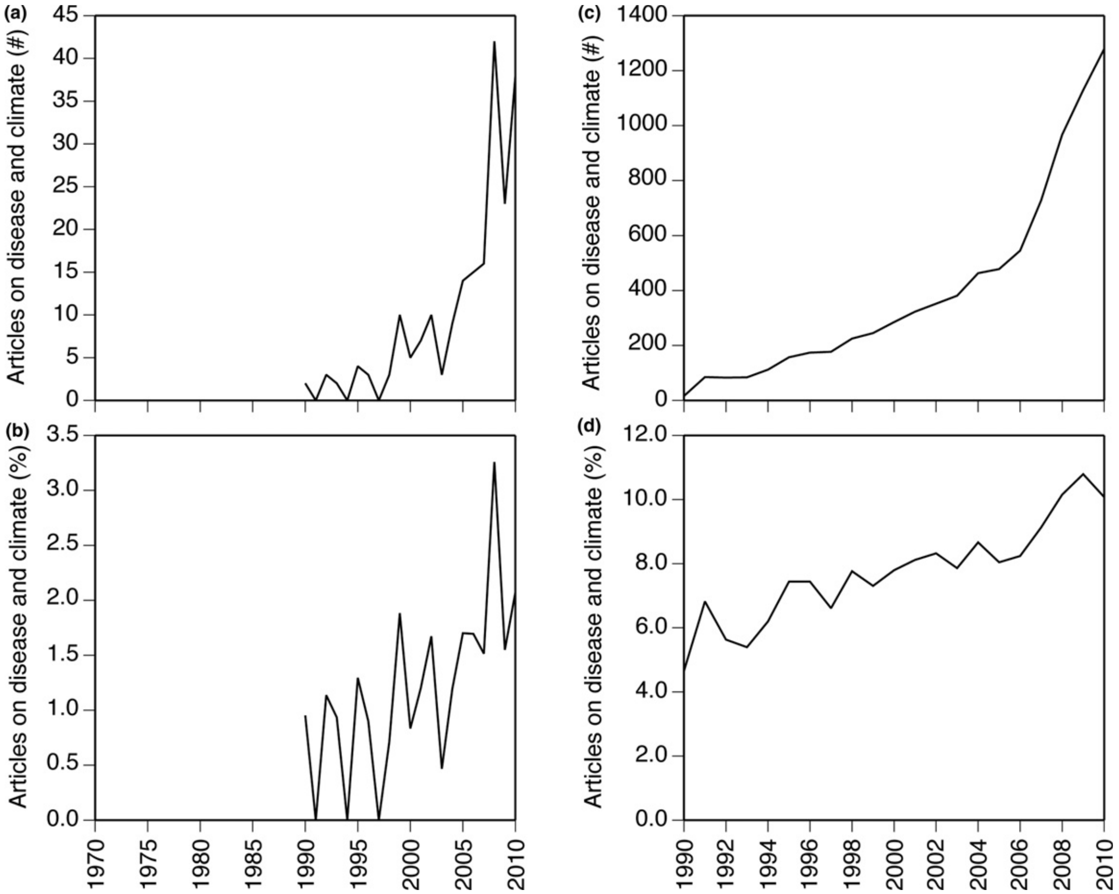

Figure 2 Long-term publication trends for climate-driven effects on infectious diseases. (a) Number of articles with disease in title (1970–10); best model did not need a smoothing term, but included a moving average term of 1 ($p = 0$, $q = 1$); R^2 adj = 0.87, $n = 41$; s(YEAR): edf = 1, $P < 0.00001$. (b) Proportion of articles with disease in title (1970–2010); best model included a smoothing term and a lag of 2 years ($p = q = 2$). R^2 adj = 0.72, $n = 41$; s(YEAR): edf = 3.32, $P < 0.00001$. (c) Number of articles with disease in abstract or title (1990–10); best model included a smoothing term, an autoregressive term, and a moving average term of 2 ($p = 2$, $q = 1$); ($p = 0$, $q = 2$); R^2 adj = 0.99, $n = 21$; s(YEAR): edf = 6.49, $P < 0.00001$. (d) Proportion of articles with disease in abstract or title (1990–2010); best model included no smoothing term and no autoregressive or moving average terms ($p = q = 0$); R^2 adj = 0.84, $n = 21$; s(YEAR): edf = 1, $P < 0.00001$.

majority of the published research was suggestive of a positive linkage between climate and disease, the mechanisms underlying these associations varied across systems. For vector-borne pathogens, the most commonly cited mechanism was climate-mediated effects on vector abundance (Møller 2010; Stenseth et al. 2006). Specifically, mild winters and wet years were reported to enhance survival and reproduction of vectors, potentially contributing to greater disease risk. Climate also had a positive direct effect on some pathogens. Increasing temperatures enhanced the growth or replication rate of the pathogen in several studies (Bruno et al. 2007; Karvonen et al. 2010). However, increased temperature also decreased the prevalence of other pathogens due to a shift away from optimal growing conditions (Karvonen et al. 2010) or led to greater mortality rates when outside of the host (Ibelings et al. 2011). There was also evidence that climate altered host physiology. For instance, increasing temperatures were associated with immunosuppression of the host, which resulted in greater disease incidence (Bruno et al. 2007; Harvell et al. 2009).

Collectively, these results suggest that there is general support for a positive association between temperature and precipitation change for diseases caused by a variety of parasite types (e.g., viruses, bacteria, fungi, protozoans, nematodes), within a diverse range of host taxa (e.g., invertebrates, fish, birds, mammals), and ecosystems (e.g., freshwater, marine, terrestrial), but the mechanisms underlying these associations are varied and far from universal. Several studies suggested that positive associations between temperature and coral diseases may be the result of temperature-driven reductions in host immune responses (Bruno et al. 2007; Harvell et al. 2009). By contrast, associations between climate and diseases of endotherms (e.g., birds and mammals) were more often thought to be driven by changes in parasite or vector populations (Møller 2010; Hudson et al. 2006). Still other studies indicate the potential for more complex relationships between climate and disease risk, governed by the timing of host infection (Ibelings et al. 2011).

It is important to note that surprisingly few long-term studies have been conducted (and published) based on wildlife populations. Although a positive association between changes in temperature and precipitation and wildlife diseases was supported by this analysis, the paucity of research limits our

Table 1 Summary of multi year field studies examining the effects of climate change variables on disease dynamics in wildlife hosts. For each study, the effects of climate change on disease dynamics are summarized as either positive, negative, or no change. For studies that examined multiple pathogens, the results are summarized across all the pathogens

				Association with the variable		
Host	*Disease or pathogen*	*Location*	*Climate variable(s)*	*Positive*	*Negative*	*No change*
Coral[a]	White syndrome	Australia's Great Barrier Reef	Temperature increase	1	0	0
Coral[b]	Atramentous necrosis	Australia's Great Barrier Reef	Temperature increase and precipitation increase–decrease	1	0	0
Coral[c]	Caribbean yellow band disease	Caribbean	Temperature increase	1	0	0
Daphnia pulicaria[d]	Chytridiomycete parasitoid	The United States	Temperature increase and precipitation increase–decrease	1	0	1
Diatoms[e]	Chytrid infection	The Netherlands	Temperature increase	0	1	0
Snow and Tanner crabs[f]	Bitter crab disease	Newfoundland	Temperature increase	1	0	0
Atlantic salmon and sea trout[g]	Bacterial and protozoan infection	Finland	Temperature increase	1	1	1
Barn swallow[h]	Parasite assemblage	Denmark	Temperature and precipitation increase–decrease	1	1	1
European rabbits[i]	Gastrointestinal nematodes	Scotland	Temperature and precipitation increase–decrease	1	0	1
Sheep[j]	Ovine parasitic gastroenteritis	Great Britain	Temperature increase	1	0	0
Great gerbils[k]	*Yersinia pestis*	Kazakhstan	Temperature and precipitation increase–decrease	1	0	0

[a] *Bruno, J. F., E. R. Selig, K. S. Casey, C. A. Page, B. L. Willis, C. D. Harvell, H. Sweatman, and A. M. Melendy, 2007: Thermal stress and coral cover as drivers of coral disease outbreaks.* PLoS Biol., ***5***, *1220–1227.*

[b] *Haapkyla, J., et al. 2011: Seasonal rainfall and runoff promote coral disease on an inshore reef.* PLoS One, ***6***.

[c] *Harvell, D., S. Altizer, I. M. Cattadori, L. Harrington, and E. Weil, 2009: Climate change and wildlife diseases: When does the host matter the most?* Ecology, ***90***, *912–920.*

[d] *Johnson, P. T. J., A. R. Ives, R. C. Lathrop, and S. R. Carpenter, 2009: Long-term disease dynamics in lakes: causes and consequences of chytrid infections in* Daphnia *populations.* Ecology, ***90***, *132–144.*

[e] *Ibelings, B. W., A. S. Gsell, W. M. Mooij, E. van Donk, S. van den Wyngaert, and L. N. D. Domis, 2011: Chytrid infections and diatom spring blooms: paradoxical effects of climate warming on fungal epidemics in lakes.* Freshwater Biol., ***56***, *754–766.*

[f] *Shields, J. D., D. M. Taylor, P. G. O'Keefe, E. Colbourne, and E. Hynick, 2007: Epidemiological determinants in outbreaks of bitter crab disease (*Hematodinium *sp.) in snow crabs* Chionoecetes opilio *from Conception Bay, Newfoundland, Canada,* Dis. Aquat. Org., ***77***, *61–72.*

[g] *Karvonen, A., P. Rintamaki, J. Jokela, and E. T. Valtonen, 2010: Increasing water temperature and disease risks in aquatic systems: climate change increases the risk of some, but not all, diseases.* Int. J. Parasitol., ***40***, *1483–1488.*

[h] *Moller, A. P., 2010: Host–parasite interactions and vectors in the barn swallow in relation to climate change.* Glob. Change Biol., ***16***, *1158–1170.*

[i] *Hudson, P. J., M. Cattadori, B. Boag, and A. P. Dobson, 2006: Climate disruption and parasite-host dynamics: patterns and processes associated with warming and the frequency of extreme climatic events.* J. Helminthol., ***80***, *175–182.*

[j] *van Dijk, J., G. P. David, G. Baird, and E. R. Morgan, 2008: Back to the future: developing hypotheses on the effects of climate change on ovine parasitic gastroenteritis from historical data,* Vet. Parasitol., ***158***, *73–84.*

[k] *Stenseth, N. C., et al. 2006: Plague dynamics are driven by climate variation.* Proc. Natl. Acad. Sci. USA, ***103***, *13110–13115.*

ability to generalize the observed trend across the diversity of taxa that are likely to be influenced by any changes in local and regional climate. As in any survey of the literature, a significant concern is publication bias (Gates 2002). Interestingly, studies that reported negative or no associations with one disease were often accompanied by results that showed a positive association with changes in temperature and precipitation for a different pathogen. While it is difficult to determine whether publication bias exists in the literature examining climate-mediated effects on disease, particularly when so few studies have been published, the existing experimental literature suggests that climate has the potential to influence disease in a variety of positive as well as negative directions. Thus, we suspect that publication bias toward reporting increases in disease with temperature increases and precipitation changes may be a contributing factor in our survey results. Alternatively, however, given the many concurrent factors that can influence infection alongside climate, it may be that detecting climate-based effects on disease in naturally occurring populations is frequently obscured by concurrent changes in other driver variables. Taken together, these two observations underscore the need for more long-term studies of disease and climate that incorporate multiple pathogens and host species to provide a more robust test of the hypothesized role of climate shifts in disease emergence.

4.06.4 Future Research Directions

Interest in the role of climate in disease emergence has grown considerably over the past two decades. Surprisingly, however, relatively few field studies have quantitatively evaluated the role of shifts in temperature, precipitation, or their variability in affecting diseases of wildlife. For the few studies that have examined the responses of host–pathogen interactions in wildlife, there was a general trend for increased pathogen prevalence with temperature increases and precipitation changes. However, the paucity of data on wildlife pathogens limits the generalizations that can be made and presents an important quandary: Why are there relatively few empirical studies examining the linkage between climate and disease emergence in wildlife populations, particularly given a nearly >40-year history of climate data? There could be a number of explanations. It is possible that the data simply do not exist at this time. Although researchers identified the threat of changes in local and regional climate decades ago, there could be too few long-term data sets on disease or pathogen prevalence in wildlife populations to make meaningful assessments of linkages between climate and disease emergence (e.g., Johnson et al. 2009). It is also possible that long-term data sets exist, but the results do not support the hypothesis that climate change mediates disease emergence. Consequently, researchers could be less likely to publish these results, which are counter to most theoretical predictions (Ioannidis 2005; Rosenthal 1979). Lastly, the complexity inherent to host–pathogen systems coupled with the multifaceted impacts of climate on these interactions could present a significant research barrier, hindering the ability of researchers to detect climate-mediated effects even when present. Below, we suggest future directions that could help expand our understanding of climate-mediated effects on disease and overcome some of these potential challenges.

4.06.4.1 Greater Emphasis on Long-Term Data

An obvious obstacle to assessing the effects of climate on infectious diseases is the lack of long-term data. As experimental and theoretical approaches continue to advance our understanding of the potential mechanisms that could drive changes in disease incidence with climate, it is imperative that long-term field studies are implemented to test these mechanisms in wildlife and the human disease systems. For instance, the U.S. National Science Foundation has sponsored the formation of the National Ecological Observatory Network (NEON; www.neoninc.org/), which is specifically designed to assess the impacts of climate on ecological systems, including infectious diseases at sites across the United States. By establishing disease monitoring programs at sites that span a diversity of ecosystems and component species, there is the opportunity to gain broad insights into the role that climate plays in disease dynamics. For example, similarities and differences in disease outcomes can be compared across different host–pathogen systems or for particular host–pathogen systems that are embedded within different environmental contexts. This information may help to address potential publication bias in the literature by generating additional data sets for publication and examining a diversity of host–pathogen systems. As such, this research has the potential to provide comprehensive tests of the hypothesized role of climate in disease emergence across host species and pathogen types.

4.06.4.2 Trait-Based Approaches and Risk Matrices

The complexity of many disease systems combined with uncertainties in climate predictions pose significant challenges for predicting which diseases could respond positively or negatively to changes in local and regional climate. Climate can alter disease risk by affecting host vulnerability to infection (e.g., via changes to host resistance or tolerance), changing parasite or vector populations (e.g., via replication, infectivity, or habitat availability), or shifting the timing or location of host–parasite interactions (e.g., via phenological or range shifts). Some hosts, such as corals may be particularly sensitive to warm temperatures at which their associated pathogens are still able to thrive (Harvell et al. 2009). On the opposite end of the spectrum are certain fungal pathogens that are adapted to cooler temperatures and may decline with warmer temperatures (Sturrock et al. 2011). Trait-based approaches to understanding host immunity and/or disease risk are gaining increased attention (Cronin et al. 2010; Johnson et al. 2012) and may prove useful in developing a 'risk matrix' of climate impacts on disease (Rohr et al. 2011). Such trait-based approaches to thermal sensitivity of hosts and parasites could also be combined with knowledge of species' ranges and habitat quality to further narrow our predictions of where climate-driven increases in disease risk for a given species are the greatest threat. For instance, hosts living at the limits of their ranges, or in habitats that are experiencing other forms of environmental degradation may be particularly sensitive to alterations in local and regional climate (Portner and Farrell 2008), making them more susceptible to disease.

4.06.4.3 New Analytical Techniques to Address Climate–Community Interactions

A key gap in our understanding of the ecological effects of climate involves identifying how shifting temperatures and rainfall could influence species interactions and community dynamics (Gilman et al. 2010). Because infectious diseases are governed by intra- and interspecific transmission events, understanding how climate affects such interactions is a critical component of determining how disease risk may be altered (Rohr et al. 2011; Paull and Johnson 2011a,b). Individual species can have different physiological, phenological, and distributional responses to changing temperatures and precipitation, which would shift the character and timing of interspecific interactions, as well as the suite of interacting species (Walther et al. 2002; Parmesan 2006; Parmesan et al. 2011; Parmesan and Yohe 2003; Post et al. 2009; Hoegh-Guldberg and Bruno 2010; Woodward et al. 2010). Few studies, however, have considered how these phenomena will ultimately influence disease.

Improving our understanding of how climate could alter host–parasite interactions will require a more nuanced empirical understanding of the climate-dependence of organismal physiology, and a better incorporation of these parameters into simplified host–parasite models and community modules (Gilman et al. 2010; Fuller et al. 2010; Helmuth et al. 2010; Helmuth et al. 2011). A simplifying assumption made in numerous climate-disease studies is that organismal growth and development has a positive linear relationship with temperature (Rohr et al. 2011). In reality, however, increases in temperature enhance the performance of organisms up to a critical threshold after which performance declines (Bruno et al. 2007; Rohr et al. 2011; Codeco et al. 2008; Angilletta 2009). Determining how the shape and range of these thermal performance curves vary across species will be important for assessing whether climatic conditions could increase or reduce the growth and mortality rates or stress experienced by hosts, vectors, and parasites (Rohr et al. 2011). Precipitation is a similarly important driver of organismal physiology, governing the timing of reproduction, as well as growth and development in many species (Parmesan 2006). If hosts, vectors, and parasites respond differently to changes in temperature and precipitation, this can lead to shifts in the timing of host–parasite interactions, transmission rates, and changes in relative abundance (Ostfeld 2009; Møller 2010; Purse et al. 2005; Ibelings et al. 2011). Thus, models incorporating these physiological changes in all organisms involved in the transmission cycle will expand our ability to predict climate-driven changes to select well parameterized disease systems (Rohr et al. 2011; Paull and Johnson 2011a,b).

Limitations on the ability to obtain parameter estimates in many disease systems will make incorporating all of these physiological responses challenging, highlighting the need to develop simplifying assumptions that do not obscure the most important drivers of change. Thus, using theoretical 'community modules' to test which of these physiological responses are likely to have the largest effect will be an important step toward determining which parameters should be included in the model. Gilman et al. (2010) suggest some generalized ecological community modules that could be adapted to incorporate disease systems more specifically. For example, modeling the effects of climate on transmission between two hosts and a vector or between intermediate and definitive hosts could offer insight into which drivers have the strongest effect on disease transmission in those systems. These effects could then be scaled up to explore disease dynamics within larger communities that are influenced by climate shifts.

4.06.4.4 Greater Synthesis

A growing body of evidence shows that local and regional climatic conditions affects the physiology and phenology of most species, leading to effects on species ranges, interactions, and evolutionary processes (Parmesan 2006; Parmesan amd Yohe 2003; Visser and Both 2005). The need to synthesize this information into a cohesive management framework has inspired recent attempts to develop vulnerability assessments for the responses of species and ecosystems to climate (Heikkinen et al. 2010; Huey et al. 2009; Dawson et al. 2011). Such assessments can provide crucial information about where management efforts may be most efficiently allocated. These analyses have predominately been completed for free-living species, yet parasites and pathogens also respond in nonlinear and idiosyncratic ways to climate (Rohr et al. 2011; Roy et al. 2004). Although the diversity and complexity of host–pathogen interactions presents a significant challenge to developing vulnerability assessments, a greater emphasis on conducting comparisons across host–pathogen systems that differ in key ecological (e.g., environmental backgrounds) and epidemiological (e.g., transmission dynamics) parameters will help to provide general insights into the link between climate change and disease emergence. Efforts to adapt these analyses to assess the infectious diseases that are most likely to emerge as a result of climate change will benefit managers seeking to mitigate climate-driven changes to diseases of humans, plants, and wildlife. However, our ability to meaningfully implement vulnerability assessments is contingent on the initiation of more long-term research on host–pathogen responses to climate.

4.06.5 Conclusion

The debate continues over the effects of climate on the distribution and severity of diseases (Wilson 2009). It is clear that climate has both direct and indirect effects on disease incidence by influencing the environmental context in which host–pathogen interactions are embedded. However, simple generalizations about whether climate has played a role in disease emergence are precluded by the complexity associated with host–pathogen interactions within communities, the confounding influence of multiple and concurrent environmental change drivers, and the lack of published long-term studies. To expand our understanding of climate-mediated effects on disease, there is a need to integrate empirical and theoretical research across multiple scales (e.g., organism physiology to interacting communities), which will require greater collaborative efforts involving researchers with diverse expertise.

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Center for Disease Control and Prevention Climate Change Website (http://www.cdc.gov/climatechange/)

Ecologists Question Effects of Climate Change on Infectious Diseases (http://www.esa.org/pao/newsroom/pressReleases2009/04012009.php)

4.07 Extreme Climatic Events

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Glossary

Climate extreme A statistically rare or unusual occurrence, with respect to the historic distribution of climate parameters of a system, of one or a combination of climate parameter values (e.g., mean, minimum or maximum temperature); examples include heat waves, severe drought, and periods of heavy rainfall. A climate extreme differs from a weather extreme in that it captures average climate conditions over longer periods of time, whereas weather extremes refer to unusual occurrences in precipitation or temperature on a day-to-day basis.

Extreme climatic event An episode or occurrence in which a statistically rare or unusual climatic period alters ecosystem structure and/or function well outside the bounds of what is considered typical or normal variability.

4.07.1 Introduction

Human activities are changing the climate system (IPCC 2007; Kabat et al. 2004; NRC 2005), including changes in the composition of the earth's atmosphere, through an increase in greenhouse gas emissions resulting from energy production and biomass burning, aerosol emissions, and land use change. Although, there remains uncertainty as to the rate and magnitude of changes in climate statistics, it is clear that human-caused changes are already occurring and will continue over the rest of the current century. Hence, there is a pressing need to better understand and predict the consequences of possible climate changes on ecological systems, even if the specific projections have not been shown to have regional predictability (NRC 2001; Lucier et al. 2006; Pielke et al. 2012).

The possible change of climate extremes, such as heat waves, periods of heavy rainfall (and associated floods), and severe drought, is now recognized as one of the most important aspects of concern with respect to climate by the broader scientific community (Solomon et al. 2007; Jentsch et al. 2007; Jentsch and Beierkuhnlein 2008; Smith 2011a,b; IPCC 2012). This is, in part, because climate extremes are expected to have large and widespread impacts on both managed and natural ecosystems, and the services they provide (Easterling et al. 2000; Parmesan et al. 2000; Ciais et al. 2005; Smith 2011b), as well as profound economic costs, and significant consequences for human welfare (Karl and Easterling 1999; Easterling et al. 2000; Beniston and Stephenson 2004; Garcia-Herrara et al. 2010). Changes in climate means and variability could increase both the probability of occurrence and magnitude of these extremes in the future (Mearns et al. 1984; Houghton et al. 2001; Solomon et al. 2007). Thus, climate extremes will continue to figure prominently as a diverse set of drivers of ecological dynamics in the coming decades.

In this chapter, I first provide some historical context for the study of climate extremes, followed by an overview of the ecological consequences of climate extremes, and a framework for assessing their impacts on ecosystem function and services. I conclude by discussing future research needed for advancing our understanding of the effects of climate extremes on ecosystems.

4.07.2 The Emerging Field of Climate Extremes Research

The ecological consequences of extremes or extreme events, particularly those associated with climate (e.g., floods, drought, hurricanes), have long been of interest to ecologists, with the ecological responses to climate (weather) extremes (droughts, floods, windstorms, etc.) often studied within the field of disturbance ecology (Pickett and White 1986). Evolutionary ecologists have similarly recognized the role of climate extremes as potential drivers of selection, trait fixation, and speciation (Gutschick and BassiriRad 2003; Combes 2008). Despite the long-standing recognition of their ecological importance, the study of climate extremes, as a threat to

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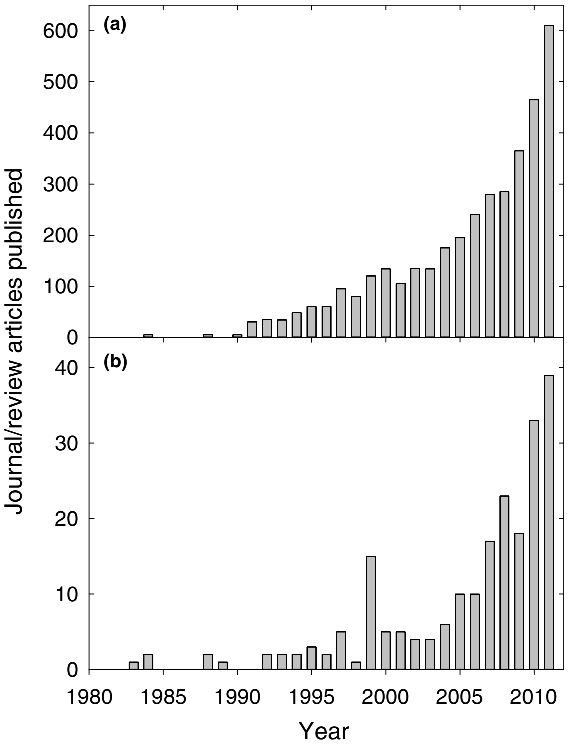

Figure 1 Results from a Web of Science search by topic (a, 3767 records) and by title (b, 216 records) for the terms "climate extreme*," "extreme climat(e/ic)," "weather extreme*," and "extreme weather." Search results were further refined by including only journal and review papers within the categories ecology, environmental sciences, or water resources. The latter filters were used to exclude climatological and meteorological papers in order to emphasize trends in ecological and environmental research. The time period for the search was "all years in database." Only the last 30 years are shown for simplicity, as very few records occurred before this time period.

ecosystem function and services, has only recently gained momentum in the field of ecology.

To illustrate this recent increase in interest, a Web of Science search was conducted within ecological and environmental journals on the terms 'climate extreme(s),' 'extreme climat(e/ic),' 'weather extreme(s),' and 'extreme weather' – terms which have now become part of the lexicon of climate (Figure 1). The goal of this search was to exclude climatological and meteorological studies and distinguish between the more traditional ecological research papers focused on specific types of climatic events (such as floods, droughts) from papers published that include a broader conceptualization of climate extremes within the context of climate. The search was first conducted more generally to evaluate trends in the topical use of these terms anywhere in published papers (Figure 1(a)). The search was then modified to include only those papers with these terms in the title (Figure 1(b)), in order to identify trends in published works specifically focused on climate extremes.

The search revealed that although use of 'climate extremes' (and associated terms) extends back over 60 years in the Web of Science database, more general interest and recognition of climate extremes only began in earnest in the early 1990s, and since the mid-2000s has increased exponentially (Figure 1). Mirroring this more general interest in climate extremes, the trends in papers published that are primarily focused on climate extremes, as evidenced by use of the terms in the title (Figure 1(b)), illustrates how young and emergent this field is within the ecological community. For example, there was an average of three papers per year published with climate extremes in the title in the 1990s, but this increased 10-fold to 39 in 2011. Interestingly, this number is still only approximately 10% of the 380 papers in 2011 that more generally included the term climate extremes in the body of the paper (Figure 1(a)). This suggests that recognition of the importance of climate extremes far outpaces studies specifically focused on this well-recognized aspect of climate.

4.07.3 Ecosystem Impacts of Climate Extremes

The recent increase in recognition of the ecological importance of climate extremes (Easterling et al. 2000; Jentsch and Beierkuhnlein 2008) has led to a number of studies focused on understanding organismal to ecosystem impacts of climate extremes (Jentsch et al. 2011). Smith (2011b) reviewed some of these studies and found that the impacts of climate extremes on ecosystems can be quite variable. For example, a period of climate extremity, such as a heat wave or severe drought, can result in widespread mortality of key populations or species (Weaver 1968; Breshears et al. 2005; Bigler et al. 2006, 2007; Giltin et al. 2006; Miriti et al. 2007; Thibault and Brown 2008), dramatic alterations in community structure (species diversity, abundance of species), and ecosystem functions (MacGillivray et al. 1995; White et al. 2000; Haddad et al. 2002; Ciais et al. 2005; Mueller et al. 2005; Evans et al. 2011; Kreyling et al. 2011), increased vulnerability to invasion by exotic species (Jimenez et al. 2011), and landscape-scale shifts in ecotone boundaries (Allen and Breshears 1998). However, the effects of these climate extremes also can be quite limited and/or merely transient, with only negligible ecosystem impacts (Van Peer et al. 2001, 2004; Marchand et al. 2005, 2006a,b; Milbau et al. 2005; Bokhorst et al. 2008; Kreyling et al. 2008; Arnone et al. 2011; Jentsch et al. 2011).

This apparent variability among ecosystems, in their sensitivity to climate extremes, raises important questions about the determinants of ecosystem vulnerability to these periods of climate extremity and our ability to assess possible ecosystem responses to alterations in climate extremes. Several questions arise including: Are there characteristics or factors that make ecosystems more or less vulnerable to climate extremes? Are there thresholds of ecosystem response to periods of climate extremity? How extreme does a climate event, such as a severe drought, flood or heat wave, need to be to push systems across these thresholds or evoke large ecological responses?

Addressing these and related questions is particularly challenging due to the inherent context dependency of climate extremes (Smith 2011b). This context dependence arises in two ways. By definition, a climate extreme represents the tails of the distribution of a climatic parameter (e.g., mean temperature) or a combination of climate parameters (Figure 2), as in the case of severe drought, which involves low precipitation amounts and high temperatures (Easterling et al. 2000; Jentsch et al. 2007). Thus, statistical rarity is a key feature of climate extremes, and accordingly identifying what constitutes 'rare' requires extensive

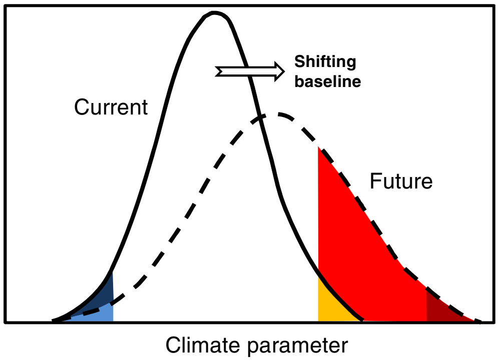

Figure 2 Climate extremes (e.g., defined as those with $\leq$5% statistical probability of occurrence; dark blue–yellow portions of the "current" climate curve, light blue–dark red portions of the "future" climate curve) could become more frequent and intense with changes in climate means and/or alterations in the distribution of climate variables (red shaded area). A similar shift also could occur to the left in the above figure, but only the right shift is shown for simplicity. With changes in climate means (represented by the shift in the future curve to the right) and variability (represented by a widening in the future distribution), the climatic baseline would shift (arrow), and consequently far fewer climate conditions would be deemed extreme based on the statistical definition of rarity (dark red shaded area), even though organisms in the system would be experiencing many more periods of climatic extremity (red + dark red shaded areas). Establishment of a fixed and standardized climatic baseline for ecological studies will improve our ability to interpret how climate extremes may be altered and will impact ecosystems with changes in climate statistics. From Smith, M. D., 2011a: The ecological role of climate extremes: current understanding and future prospects. *J. Ecol.*, **99,** 651–655.

knowledge of the climate record, which is often lacking for many ecosystems. However, what constitutes 'extreme' depends not only on the climate record but also what the system has experienced previously – both in the short-term and the long-term. In the short-term, a severe drought that follows several years of below average precipitation, for example, may have different impacts than one that occurs right after a wet period. When considering climate over the long-term, an ecosystem with high interannual variability may respond differently to a climate extreme than one that has low variability, for example. Thus, the 'extremeness' of a climate event and the consequent vulnerability of the system to that event will depend not only on whether a climate extreme is rare from a statistical sense but also how those conditions relate to both long-term and short-term climatic variability experienced by the ecosystem. The expectation is that, if the climate extreme alters environmental conditions well outside the bounds typically experienced by a system, then an 'extreme' (statistically unusual) ecosystem response will result. In other words, a climate extreme that causes widespread mortality of species, for example, as opposed to one that just merely alters physiology of individuals. Without knowledge of both aspects of context dependence, it is difficult to determine whether variability in the vulnerability of ecosystems to climate extremes is due to some ecosystems having characteristics that make them particularly resistant (or susceptible) to a climate extreme versus the possibility that an ecosystem did not experience truly extreme climate conditions.

Thus, as I have argued previously (Smith 2011b), in order to advance our understanding of the impacts of climate extremes on ecosystems and what factors underlie ecosystem vulnerability to climate extremes, we must be able to identify when climate conditions are extreme, determine when extreme ecosystem responses occur, and most importantly, be able to attribute the climate extreme as the driver of an extreme ecosystem response. Smith (2011b) refers to the latter as an extreme climatic event (ECE). The identification and attribution of each of these requires that there are clear definitions of what constitutes a climate extreme, an extreme ecological response, and an ECE.

4.07.4 Definitions of Climate Extremes, Extreme Ecological Responses, and ECEs

Defining a climate extreme is much more straightforward than defining what constitutes an extreme ecological response (Smith 2011a). As indicated above, definitions of climate extremes have generally been based on the statistical distribution of a climate variable for any system (Figure 2), with extremes represented by the tails of distribution of a particular climate parameter (e.g., mean, maximum, minimum temperature) or combination of parameters (as in the case of a drought). A climate extreme differs from a weather extreme in that, it captures average climate conditions over longer periods of time, whereas weather extremes refer to unusual occurrences in precipitation or temperature on a day-to-day basis. The expectation with any change in climate means and/or variability is that climate extremes would become more frequent and intense in the future (Figure 2; Meehl et al. 2000). Due to the statistical nature of the definition, this increase in frequency and intensity must be predicated on a fixed frame of reference or climatic baseline (e.g., the historic climate record for a site). For example, a shift in mean temperatures toward warmer conditions would result in a greater number of high temperature extremes based on the current statistical distribution (red shaded area, Figure 2), particularly if variability around the mean also is increased. However, if the climatic baseline is allowed to shift, as would occur with increases in the means and/or alterations in the distributions of climate variables, then substantially fewer climate conditions would be deemed extreme based on, for example, a $\leq$5% statistical probability of occurrence (dark red shaded area, Figure 2). This statistically based outcome would occur even though periods of climate extremity would actually be much more common from the perspective of the organisms in the system (e.g., red + dark red shaded areas, Figure 2) relative to the conditions they had previously experienced. In other words, to be ecologically meaningful, the statistical attributes of the long-term climate that the biota have been experiencing historically (e.g., prior to changing climate statistics) should be similar to those used to determine extremity. Therefore, there is a clear need to establish relevant or fixed climatic baselines for identifying climate extremes (Smith 2011a). An example of a fixed baseline that has proven to be invaluable is the ca. 280 ppm pre-industrial atmospheric CO_2 concentration for studies of the impacts of increases in atmospheric CO_2 on ecosystems. For climate extremes research, system-specific climatic baselines would provide the necessary benchmarks for assessing how the frequency and magnitude of extremes may change with current and future scenarios of climate, and allow for the determination of when a period of climatic extremity has occurred for a particular ecosystem.

In contrast to climate extremes, defining an extreme ecological response is more difficult (Gutschick and Bassirirad 2003), as it depends on both the ecological system in question and the timescale considered. For example, the drivers and the magnitude of a statistically extreme response for a desert grassland has the potential to be very different than that for a tropical forest. Moreover, the extremity of a response for a particular system may change considerably if one considers the 20 years of historic variability versus a millennial scale paleo-record for the same site. From an ecological response perspective, Gutschick and BassiriRad (2003) defined an extreme event (climatic or otherwise), as one in which the ability of an organism or population to acclimate is substantially exceeded, with often persistent effects after the event, resulting in longer-term impacts on fitness. The limitation of this definition is that the most extreme ecological response (e.g., left tail of the distribution, **Figure 3**) is mortality of individuals or entire populations. However, depending on the role and abundance of the species impacted, such responses may or may not result in changes at the community or ecosystem level that can be distinguished from background variability. For example, mortality of individuals in a population, or even entire populations within a community, may have negligible impacts beyond the particular population or populations affected, if the impacted species are rare overall or have minimal roles in key ecosystem processes.

Smith (2011b) argued that for an ecological response to be considered extreme it should include responses beyond the individual or population level, including substantial changes in community composition and structure caused by the reordering of key or common species in the community, widespread species loss, and/or invasion by novel species, with subsequent large and potentially persistent effects on ecosystem structure and function (**Figure 4**, Smith et al. 2009). While mortality of individuals and/or populations and associated changes in fitness may underlie these higher-level responses, particularly if, for example, dominant species are impacted (e.g., Allen and Breshears 1998), an extreme ecological response should be one in which ecosystem structure and/or function is altered well outside the bounds of what is considered typical or normal variability and cascades across multiple hierarchical levels (e.g., population, community, and ecosystem). As with climate extremes, characterizing the distribution of ecological responses for an ecosystem is critical for determining when an extreme ecological response occurs. However, this characterization will be a significant challenge for many ecosystems as many ecological studies are of short duration. The inherent difficulty of describing the potential range of ecological responses of any ecosystem emphasizes the value of long-term studies of a broad range of ecosystems, which can provide the necessary context for interpreting ecosystem responses and a baseline for evaluating extremeness of ecological responses (Callahan 1984).

Not all climate extremes result in extreme ecological responses as defined above (**Figure 4**, Smith 2011b). However, being able to attribute a period of climate extremity as the driver of an extreme ecological response is critical for determining what factors may contribute to differential vulnerability of ecosystems to climate extremes. Thus, although the term 'extreme climate (or climatic) event' is often used interchangeably with climate extremes in the literature, the term 'extreme climatic event' should only be used in the case where an extreme ecological response results from a climate extreme. Given this, Smith (2011b) defined an ECE as an episode or occurrence in which a statistically rare or unusual climatic period results in an alteration in ecosystem structure and/or function well outside the bounds of what is considered typical or normal variability (**Figure 4**). The use of 'event' denotes the nominal short duration of the occurrence (discreteness) relative to the magnitude of its effects (Jentsch et al. 2007). Moreover, this definition emphasizes the need to define ECEs synthetically, from both the driver (occurrence) and response (effect) perspectives (**Figure 3**). Because extreme ecological responses are characterized by profound alterations in ecosystem function and structure that are driven by changes in species abundances, loss of key species and/or invasion by new species with different functional traits, ECE's are likely to result in periods of prolonged ecosystem recovery, significant hysteresis, and/or persistent state changes (**Figure 4**; e.g., Allen

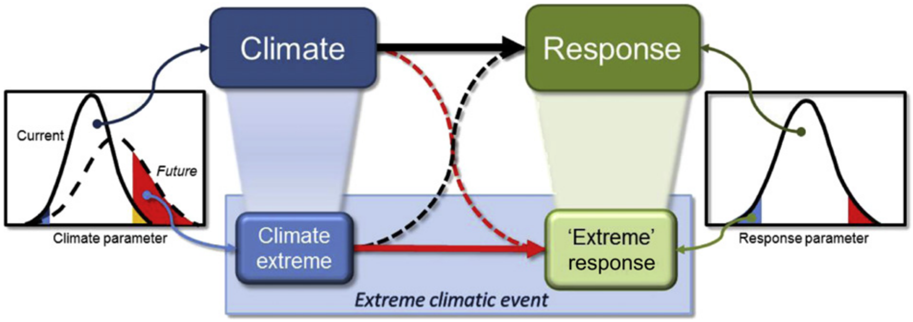

Figure 3 Changes in climate means and variability could result in a response that is well within the range of variability for a system (solid black arrow) or one that is extreme (represented by tails of the distribution on the right, dashed red arrow). Similarly, climate extremes (represented by tails of the distribution on the left) may (solid red arrow) or may not (dashed black arrow) result in an ecological response that is outside the typical or normal range of variability for a system. An extreme climatic event (ECE) is defined synthetically as the case in which an extreme ecological response can be directly attributed to a period of climate extremity. From Smith, M. D., 2011b: An ecological perspective on extreme climatic events: a synthetic definition and framework to guide future research. *J. Ecol.*, **99,** 656–663.

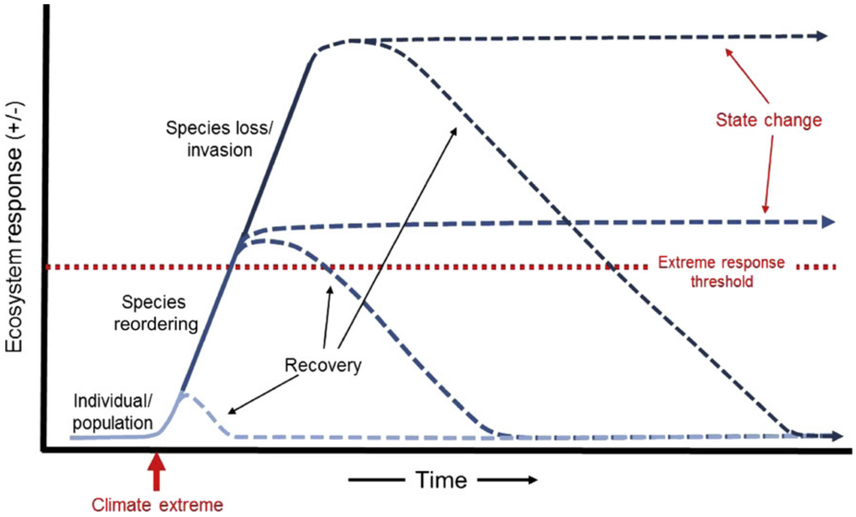

Figure 4 A framework for assessing ecosystem responses to climate extremes. A period of climate extremity that primarily affects individual-level responses (physiology, growth, fitness) of particular organisms–populations will have a smaller effect (positive or negative) on ecosystem processes (e.g., productivity, nutrient cycling) than one that results in large shifts in species abundances (species reordering), or in local extinction of species or invasion by others. An extreme climatic event is an episode or occurrence in which a period of statistical climate extremity alters ecosystem structure and/or function outside the bounds of what is considered typical or normal variability, as a consequence of crossing an extreme response threshold (dotted red line) in which individual-level effects cascade to higher hierarchical levels to result in significant changes in community structure and large ecosystem impacts. These alterations may be characterized by prolonged recovery and/or hysteresis, or may even lead to persistent state changes. From Smith, M. D., 2011b: An ecological perspective on extreme climatic events: a synthetic definition and framework to guide future research. *J. Ecol.*, **99,** 656–663.

and Breshears 1998; Haddad et al. 2002; Mueller et al. 2005; Thibault and Brown 2008).

There are several advantages to this synthetic definition of an ECE. First, it emphasizes the requirements for extremity from both a driver and response perspectives (**Figure 3**). Second, it identifies a priori the ecological mechanisms (**Figure 4**) that can lead to an ECE. In doing so, there is a basis for distinguishing between those instances where a statistically extreme climate period does not result in an extreme ecosystem response (**Figure 3**, dashed black arrow) from those instances where it does (**Figure 3**, solid red arrow). It also provides a framework for elucidating the mechanisms (individual–population versus species reordering versus species migration) that may give rise to these alternative outcomes (**Figure 4**). Finally, the definition excludes from consideration those instances where an extreme response results from some aspect of climate (e.g., changes in climate means) other than climate extremes (**Figure 3**, dashed red arrow; see Smith et al. 2009 for examples). The latter is important because mechanisms leading to an extreme ecological response driven by a gradual and chronic change in a climatic mean may differ from those associated with climate extremes (Smith et al. 2009).

4.07.5 Application of the ECE Framework

The utility of the ECE definition and accompanying mechanistic framework above for understanding the ecosystem consequences of climate extremes can be demonstrated by considering two examples. The first is from an on-going experiment designed to examine the impacts of extreme precipitation regimes on the structure and function of the tallgrass prairie ecosystem (see Fay et al. 2000 for details). For over a decade, growing season precipitation regimes have been experimentally altered using rainfall manipulation shelters deployed over intact prairie, whereby periods of time between rainfall events have been increased by 50% without altering the total rainfall amount. The altered rainfall treatment has resulted in a three fold decrease in the mean number of growing season rainfall events, with the interval between events three times longer compared to the ambient regime. Such a regime is very different from what has been observed in the historical climate record, and thus, represents a statistical extreme (see **Figure 3** in Smith 2011b). However, the primary impact has been limited to reduced performance of only a few species (Fay et al. 2003), which has resulted on average in a 10% reduction in aboveground net productivity (Knapp et al. 2002; Fay et al. 2011). This modest alteration in ecosystem function has occurred without substantive changes in community structure, loss of species, or invasion by new species (**Figure 4**), and while the reduction in production is significant ecologically, it is well within the natural range in variability observed for this system (Knapp and Smith 2001). Thus, although a period of climatic extremity was imposed, the ecosystem appears to be relatively resistant to this type of climate extreme, and according to the definition above, the grassland has not experienced an ECE. This conclusion is based on both the lack of profound impact on the ecosystem as well as the absence of any mechanistic evidence that thresholds have been exceeded that could lead to an extreme ecological response (e.g., significant species reordering or loss of species, **Figure 4**).

A second example involves a regional climate extreme that occurred in 2002–03 across southwestern North America. This period was characterized by an extreme drought with respect to the long-term climate record and was accompanied by anomalously high temperatures. Here, the climate extreme resulted in widespread mortality of *Pinus edulis* (pinyon pine), a codominant species in pinyon-juniper woodland (Breshears et al. 2005). Such large-scale mortality events have been shown to shift ecosystem boundaries in the past (e.g., Allen and Breshears 1998) and rapidly alter ecosystem structure and function (e.g., Mueller et al. 2005), as well as significantly affect land surface conditions (Royer et al. 2011). Subsequent studies have linked pinyon pine mortality to drought-induced carbon starvation of individual trees (Adams et al. 2009). In this case, we can conclude that an ECE has occurred because the statistically defined climate extreme resulted in an extreme ecological response—one characterized by mortality of adult pinyon pine trees, which subsequently cascaded through the ecological hierarchy to have profound and potentially long-lasting impacts on the ecosystem.

The examples above can be viewed as the two alternative responses to climate extremes depicted in Figure 3. On the one hand, a statistical climate extreme was imposed, but did not result in an extreme ecological response for a tallgrass prairie ecosystem, and on the other hand, thresholds for extreme responses for pinyon-juniper woodland were clearly crossed (e.g., mortality of the dominant tree species occurred, Figure 4), resulting in large community and ecosystem impacts. A major challenge for the future will be to increase our understanding of how and why ecosystems may differ in their vulnerability to experiencing an ECE, whereby an extreme ecological response can be attributed to a climate extreme. Key to this will be placing greater emphasis on quantifying thresholds for ecological processes that when crossed may lead to extreme ecological responses, such as profound changes in ecosystem function and services. For example, in the case of the tallgrass prairie, independent studies of the responses of the dominant grasses, the dynamics of community structure, and the invasibility of the plant community all point to stability of the plant community as key to the resistance of tallgrass prairie ecosystem to the type of climate extreme imposed (Knapp et al. 2002; Nippert et al. 2009). Whether this will translate to ecosystem resistance to other types of climate extremity remains unknown and is the subject of additional research (see Figure 4 in Smith 2011b).

The value of the distinction between climate extremes and ECEs is also apparent when considering paleo-ecological records where extreme ecological responses, such as state changes or regime shifts, are a common feature; yet, these are not always attributable to climate extremes or even abrupt changes in climate (Williams et al. 2011). While there are recent examples of extreme ecological responses, such as the widespread mortality of tree species caused by extreme drought mentioned above (e.g., Allen and Breshears 1998; Breshears et al. 2005; Mueller et al. 2005; Bigler et al. 2006, 2007; Gitlin et al. 2006), the paleo-record also is replete with examples of extreme ecological responses, particularly during the late Quaternary. Williams et al. (2011) characterized these by their rapid shifts in species abundances and changes in community composition driven by large-scale mortality and species migration, resulting in persistent regime shifts or state changes. Thus, at this timescale, it is clear that extreme ecological responses as defined above can be relatively common and apparent features of ecological systems. However, as with climate extremes, a baseline for the range and magnitude of responses for ecological systems is essential for providing necessary context for determining when extreme ecological responses occur, as exemplified by the case studies from the late Quaternary and early Holocene (Williams et al. 2011).

Once climatic and ecological extremity are recognized, explicit attribution of a climate extreme as the driver of an extreme ecological response is the critical next step in determining whether an ECE has occurred (Smith 2011b). The severe drought of 2002–03 in the southwestern USA provides a clear example of an extreme ecological response that can be explicitly linked to a climate extreme. Research by Breshears et al. (2005), Adams et al. (2009), and Royer et al. (2011) demonstrates the unprecedented magnitude of mortality of the dominant tree species, *P. edulis*, as a consequence of a statistically extreme drought. Moreover, Royer et al. (2011) showed that the die-off of overstory vegetation had regional-scale effects on near-ground solar radiation, with the potential for cascading and long-term impacts for a broad range of ecological processes. Despite this and other examples of extreme ecological responses driven by periods of climatic extremity, such as severe droughts and rapid changes in temperatures (Weaver 1968; Bigler et al. 2007; Gitlin et al. 2006; Williams et al. 2011), Williams and colleagues show that demonstrating causality remains a significant challenge. This raises the questions of how often and under what circumstances do ECEs actually occur and how and why ecosystems may differ in their vulnerability to ECEs.

4.07.6 The Rarity of ECEs

While the studies described above have increased our understanding of the causes and consequences of ECEs, the rarity and a possible increase in the frequency and intensity of climate extremes in the future have prompted a number of researchers to experimentally impose climate extremes on a range of systems. For example, Arnone et al. (2011) experimentally imposed an extremely warm year on intact tallgrass prairie monoliths from Oklahoma, USA, and found an immediate and large (~30%) reduction in aboveground productivity, driven primarily by the dominant C_4 grass species in the system. However, the change in aboveground productivity was within the range of interannual variability observed for tallgrass prairie, was not persistent over time, and was not accompanied by changes in plant community structure or composition. Similarly, with statistically extreme drought events applied to constructed European grassland communities for five consecutive years, Jentsch et al. (2011) showed a lack of large effects for a broad array of ecosystem responses measured. For example, above and belowground productivity remained unchanged across all years of the study, possibly as a consequence of complementary responses among plant species, and without a concomitant change in plant community composition.

The lack of extreme ecological responses in these and a number of other recent experiments (Van Peer et al. 2001, 2004; Marchand et al. 2005, 2006a,b; Milbau et al. 2005; Bokhorst et al. 2008; Kreyling et al. 2008; De Boeck et al. 2010b) suggests that ECEs occur much less frequently than their potential drivers – the climate extremes themselves, and possibly much less frequently than suggested by observational studies and the recent paleo-record. This may be, in part, due to the fact that observational studies are often conducted only when a climate extreme evokes an obvious extreme response (e.g., widespread mortality of a species). Therefore, understanding based on observational studies may be biased toward equating climate extremes with ECEs. In addition, one might conclude from these experiments that the systems being studied are resistant to the type and/or timescale of climate extremes imposed. However, it is difficult to rule out alternatives, such as (1) that the length of these studies was insufficient to capture an extreme response for the system in question, (2) that the treatments were not extreme in terms of the historic and recent paleo-climate record or what the system and its component species had previously experienced, or (3) that unique or rare combinations of climate extremes (e.g., temperature and precipitation with severe drought, see above) may be required to evoke an extreme ecological response. Overall, these studies suggest that ECEs may be difficult to induce experimentally, and that a diversity of approaches, and a broad assessment of different types of climate extremes may be required to more fully determine the causes and consequences of ECEs.

4.07.7 Ecosystem Sensitivity to ECEs

It is clear from the section above that ECEs in which a climate extreme, such as a heat wave or drought, or combination of climate extremes results in an extreme ecological response occur much more rarely than the climatic drivers of these events. Moreover, it is likely that a single climate extreme will not generally result in an ECE unless it is of exceptional magnitude and duration. Instead, the trigger for eliciting an extreme ecological response is likely more complex, potentially involving multiple climate extremes, with the timing and sequence of these important events (De Boeck et al. 2009; De Boeck et al. 2010b). These, in turn, may interact with additional factors, such as insect outbreaks or other disturbances (Jentsch et al. 2007), as well as key attributes of the ecosystem (e.g., longevity of the dominant species, Smith et al. 2009). This complexity, as well as our inability to predict the occurrence and nature (severity, duration, etc.) of climate extremes, makes predictions as to which ecosystem will be more or less vulnerable to experiencing an ECE difficult, if not impossible. However, based on the framework presented in Figure 4, general predictions can be made about what factors may result in an ECE. For example, if a climate extreme causes widespread mortality of a dominant species, as in the case of the 2002–03 drought across southwestern North America, which caused widespread mortality of pinyon pine, then the expectation is that the ecosystem response will likely be extreme. One might expect that ecosystems dominated by species that have evolved under stressful conditions (e.g., species in arid environments) might be less susceptible to prolonged drought or heat waves, making those ecosystems more resistant to the occurrence of ECEs than those ecosystems dominated by less stress-tolerant species (e.g., species in mesic environments). Ultimately, our basic understanding of ecosystem resistance and resilience to these rare climatic periods will have to increase substantially if we are to make predictions about vulnerability.

4.07.8 Future Directions of Climate Extremes Research

It is important to consider how climate extremes and ECEs have been studied in the past, and the advantages and limitations of these approaches, to provide a context for what should be the research priorities in the future. To date, the majority of studies of climate extremes might best be described as opportunistic. These opportunistic studies arise (1) from concerted research efforts initiated after a period of climatic extremity is recognized (e.g., Allen and Breshears 1998), or (2) when a climate extreme occurs during the course of an ongoing observational or experimental study (e.g., Haddad et al. 2002; Breshears et al. 2005; van Ruijven and Berendse 2010). Although these opportunistic studies, particularly those involving observational approaches, have the ability to capture large spatial and temporal scales, they often lack replication and cannot control for characteristics of the climate extreme (type, timing, magnitude) or for other covarying factors (e.g., disturbance regimes, pest outbreaks). Such studies also are limited in their ability to assess interactions between different types of climate extremes (e.g., severe drought versus heat wave) or other factors, such as disturbance – and, of course, opportunistic studies are ultimately contingent upon a period of climatic extremity occurring during the lifetime of the study.

To overcome these limitations, there are a growing number of studies that experimentally impose climate extremes via field experiments (e.g., Marchand et al. 2005; Jentsch et al. 2007; Bokhorst et al. 2008; Smith 2011b). Indeed, many of the most recent papers identified in Figure 1(b) report on responses to experimentally imposed climate extremes. While these experiments offer the advantage of greater control over the nature of the climate extreme imposed when compared to opportunistic studies, they have to date been limited to a single climate extreme level (e.g., a 100-year drought or 30-year heat wave; but see Smith 2011b) imposed at a relatively small spatial scale. Moreover, few have considered interactions between different climate extremes (see White et al. 2000; van Peer et al. 2004; Jentsch et al. 2007; Smith 2011b) or other factors (e.g., disturbance, N deposition; e.g., Wang et al. 2008), and rarely have they addressed the role of multiple periods of climate extremity or the timing or sequence of climate extremes (De Boeck et al. 2009; Miao et al. 2009).

Opportunistic studies also are limited with respect to their ability to document the full extent of responses of ecosystems to climate extremes and their vulnerability to ECEs. However, opportunistic studies have been very successful in detailing ecosystem impacts of large magnitude as a consequence of crossing one or more thresholds for extreme responses (e.g., species reordering or species loss). Thus, they tend to capture the full magnitude of ECEs more often than experiments. This is because attention is typically not drawn to a climate extreme unless large ecosystem consequences are readily apparent (e.g., widespread mortality of a dominant species), and consequently those climate extremes that have limited impacts, or those that would not be considered ECEs by definition, tend to be understudied with the opportunistic approach. Experiments, on the other hand, have the potential to capture responses to multiple levels of climate extremes across the full range of hierarchical levels (Figure 4). Clearly, for experiments to have their greatest value, they need to be imposed at large enough scales and for long enough periods of time so that responses will not be constrained to the individual or population level (Smith et al. 2009). Otherwise, it will be difficult to determine if the lack of large impacts or the absence of evidence for exceeding extreme response thresholds is due to the limited duration, or scale of the experiment, or because the system is resistant to a particular climate extreme. Despite this limitation, experiments do have the ability, if designed properly, to identify those critical ecological thresholds that may result in an extreme response, whereas opportunistic studies do not.

Given the possible increase in frequency, severity of climate extremes (Solomon et al. 2007), and that even without such an increase climate extremes will still occur, it is clear that we should continue to opportunistically study these important drivers of ecological dynamics and change. Despite their limitations, opportunistic studies have significantly advanced our understanding of the vulnerability of ecosystems to ECEs. However, large-scale and long-term field experiments designed specifically to address critical gaps in our mechanistic understanding of how and why ecosystems may differ in their sensitivity to experiencing ECEs are more urgently needed. Some of the key features of future experiments that can address these research gaps are summarized here (see Smith 2011b):

1. For essentially all major ecosystems and biome types globally, we lack detailed knowledge of the magnitude, type, and combination of climate extremes that are most likely to result in response thresholds being exceeded and consequently for ECEs occurring. This is a daunting challenge, but at the very least, future experiments should impose periods of climate extremity at multiple levels using, for example, a replicated regression approach, whereby multiple levels of a climatic parameter can be applied in a statistically powerful way (Cottingham et al. 2005). With such an approach, climate extremes field experiments could follow the example of growth chamber and greenhouse studies that have successfully assessed response thresholds of individual species to temperature and water deficits (e.g., Hamerlynck et al. 2000; Larcher et al. 2010).
2. Also needed are experiments that impose multiple levels of climate extremity at different times of the year, or as multiple occurrences and/or in different sequences within and between years. These types of experiments can address issues of timing and the potential for antecedent (e.g., cumulative, compounded or sequential) effects of climate extremes (Paine et al. 1998; De Boeck et al. 2009).
3. Because climate extremes often occur in combination naturally, it is also critical that we continue to assess interactions between different types of climate extremes (e.g., severe drought and heat waves) at different levels of extremity. Other factors, such as changes in climate means, species diversity, trophic interactions, or disturbance regimes (see Jentsch et al. 2007), also should be considered as these may interact with climate extremes to result in the most extreme and persistent ecological responses (e.g., state changes and hysteresis, Paine et al. 1998; Smith et al. 2009).
4. Manipulations that may hasten or mimic the crossing of extreme response thresholds, such as removal of a dominant species from an ecosystem or experimentally invading systems to simulate the immigration of novel species, are needed to more mechanistically assess the vulnerability of ecosystems to experiencing an ECE.
5. Comparative studies of different ecosystems or biome types exposed to a range of climate extremes are also needed to elucidate the potential mechanisms underlying differential sensitivity, and whether these mechanisms are similar or different between ecosystems or biomes. Such comparative studies could include sites that differ in the longevity or diversity of species (Smith et al. 2009), or ecosystems that may be more or less vulnerable to climate extremes based on, for example, their sensitivity to changes in climate means.
6. Experiments need to measure ecological responses at multiple hierarchical levels (individual to ecosystem) and be conducted for sufficient periods of time, and at large enough scales to ensure that the entire range of ecological responses, and their respective thresholds are fully captured for the ecosystem in question.
7. Finally, advances in experimental infrastructure need to be made to allow researchers to impose realistic climatic extremes on organisms and entire ecosystems. Particularly challenging is imposing extremely high temperatures (more than 10 °C above ambient) under field conditions without potentially confounding artifacts (De Boeck et al. 2010a). For example, De Boeck and Nijs (2011) describe an alternative control method for infrared heaters, which are often employed to impose heat waves on terrestrial ecosystems, to avoid the potential confounding factors of plant responses to heating. Many more advances like these are needed if we are to increase our understanding of the role of climate extremes in ecological systems.

As previously mentioned, a key knowledge gap is our lack of understanding of the types and timescales of climate extremes that will lead to ECEs, as it is clear that statistically extreme climatic conditions often do not result in extreme ecological responses. Such resistance to climate extremes, and the mechanisms responsible, are as important to understand and identify as the attributes of ecosystems that make them vulnerable to experiencing an ECE. It is likely that the intensity, timing, and duration of periods of climatic extremity will interact in important and surprising ways (De Boeck et al. 2010b). However, we know very little about how ecological systems will respond to these potential interactions and whether or not they will result in extreme ecological responses. In addition, because the frequency of climate extremes could increase in the future, research is needed that addresses how repeated climate extremes may impact ecological systems and whether resistance or resilience develops over time, or if ECEs will become more frequent. Because increases in climate extremes could be accompanied by changes in climatic means, climatic variability or both, a key question is whether these aspects of climate change would increase or decrease the vulnerability of ecological systems to climate extremes. Research is also needed that addresses the role of multiple levels of diversity–genetic, species and trait, in determining the ecological and evolutionary consequences of climate extremes for organisms and their potential feedbacks on ecological processes (Schoener 2011). For example, Beierkuhnlein et al. (2011) showed how ecotypes of a key European grass species, each adapted to differing climate means, respond differently to climate extremes. However, the performance of these ecotypes could not be predicted from the climate in which they originated. This suggests that genetic and phenotypic diversity can play an important role in determining ecological responses to climate extremes, but that these effects are complex. Without doubt, much more research is needed here.

4.07.9 Conclusions

The study of climate extremes is a relatively new emphasis in ecology (Figure 1). This is despite the long-standing recognition of their importance by paleo-ecologists (Williams et al. 2011) and evolutionary biologists (Combes 2008). Although climate extremes have always been a feature of climate, their frequency of occurrence and intensity could change in the coming decades. Thus, an increasing recognition of their importance in driving contemporary ecological dynamics is needed. Ecologists need to bring a variety of approaches to expand our mechanistic understanding of how and why ecosystems may differ in their vulnerability to climate extremes. Furthermore, knowledge of the thresholds of ecological responses that may trigger dramatic ecological consequences needs to be incorporated into scenarios of future ecosystem dynamics at the global scale.

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4.08 Ecosystem Services of Energy Exchange and Regulation

D Baldocchi, Policy and Management

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Glossary

C_3 photosynthetic pathway The biochemical pathway used by most plants to fix carbon dioxide from the atmosphere. The pathway is associated with an enzyme, Ribulose Bisphosphate Carboxylase-Oxygenase (RUBISCO), which catalyzes the fixation of CO_2 and produces a C_3 compound in the early steps of the dark reactions of photosynthesis. This pathway experiences photorespiration because oxygen competes with CO_2 for RUBISCO.

C_4 photosynthetic pathway The biochemical pathway used by many tropical grasses, including corn, sugarcane, and sorghum, to fix carbon dioxide. The pathway is associated with an enzyme, phosphoenolpyruvate (PeP) carboxylase, which catalyzes the fixation of CO_2 and produces a C_4 compound in the early steps of the dark reactions of photosynthesis. This pathway does not experience photorespiration. C_4 plants maintain a lower stomatal conductance than C_3 plants and are better adapted to warmer, drier, and lower CO_2 conditions than C_3 plants.

Chronosequence A sequence of variables that change with time. Often, it pertains to studies of forests or soils across a landscape and similar climate that differ in their time since disturbance.

Leaf Area Index The projected area of leaves per unit area of ground.

Metabolism The set of chemical reactions in living organisms that maintain life.

Stomata The active pores on leaves that regulate the diffusion of CO_2, water vapor, and other trace gases into and out of leaves.

4.08.1 Introduction

Ecosystems provide a variety of services and functions that ameliorate the state of the air, land, and water, upon which life depends. A set of noteworthy ecological services that occur at local scales include regulating the supply and quality of water, soil formation, flood and erosion control, nitrogen fixation, pollination, food production, carbon sequestration, recycling of nutrients, and the provision of habitat (Costanza et al. 1997; Daily et al. 2000). At regional to continental scales, ecosystems play an integral part in determining the state of the atmosphere and climate system by regulating the exchange of energy and trace gases across the land–atmosphere interface (Arneth et al. 2010; Bonan 2008; Huntingford et al. 2011).

This chapter focuses on the exchange of energy between ecosystems and the atmosphere, as an ecosystem service. The overarching objective of this chapter is to evaluate the vulnerability of these services in the context of a changing world. To make this assessment, we first present information on the fundamental theory of energy and trace gas exchange and how they are regulated by an assortment of biophysical variables and feedbacks. We then examine the empirical and modeling literature to address such questions as: how could these services respond to climate trends and anomalies, disturbance, and land use change? Finally, we discuss how these services may be sustained under a changing climate and contribute to policy decisions by stakeholders.

4.08.2 First Principles

4.08.2.1 Why Is the Regulation of the Exchange of Energy and Trace Gases, an Important Ecological Service?

All living organisms extract energy and matter from their environment. They must do so to comply with a fundamental law of physics and biology—energy is needed to perform different forms of work (chemical, osmotic, mechanical) that enables individuals to acquire matter to grow, acquire additional resources, and out-compete their neighbors. And, they need energy to move, avoid predators, and ultimately

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reproduce, thereby passing their genes to the next generation (Chapin et al. 2002; Odum 1997).

At the most fundamental level, mass and energy exchange between the land and the atmosphere is linked to photosynthesis by plants and cyanobacteria—solar energy absorbed by leaves and cyanobacteria is used to assimilate CO_2 and synthesize reduced carbohydrates $[(CH_2O)]_n$, the prime energy source for the majority of life on Earth. The subsequent extraction of chemical energy from carbohydrates is associated with a variety of heterotrophic or chemo-autotrophic metabolisms that use a hierarchy of biogeochemical redox reactions (Burgin et al. 2011; Falkowski et al. 2008; Schlesinger et al. 2011). One consequence of life's quest for energy is the loss of a suite of trace gases (CO_2, CH_4, C_5H_8, $C_{10}H_{16}$, H_2, H_2O, H_2S, N_2, NO, N_2O, NH_3, and O_2) as organisms extract energy from carbohydrates ($C_6H_{12}O_6$) or plant detritus by oxidation reactions.

This loss of matter from the ecosystem, in the form of trace gases, however, is a gain by the atmosphere. Consequently, trace gas transfer alters the atmosphere's chemical composition and modulates its 'greenhouse' warming effect (Ramanathan 1998); polyatomic gases, like CO_2, H_2O, CH_4, and N_2O, absorb and reradiate infrared radiation. The presence of 'greenhouse' gases in the atmosphere keeps the mean temperature of Earth above freezing, keeping water in a liquid state for its ubiquitous use by life. Over geological history, the exchanges of energy and biogenic trace gases have contributed to the coevolution of life and the atmosphere's chemical composition, and together have acted to stabilize the Earth's climate and made it hospitable for life (Lenton and van Oijen 2002; Walker 1984). In addition, the production of oxygen by photosynthesis is the ecological service that is responsible for the evolutionary explosion in complex, multicelled, Eukaryotic life, which depends upon aerobic respiration (Knoll 1992). In this context, it may not be an overstatement to say that mass and energy exchange between the biosphere and atmosphere is the ultimate ecological service.

4.08.2.2 What Are Key Environmental Processes and Variables Affecting Mass and Energy Exchange?

In quantifying energy and trace gas exchange of ecosystems, we must comply with limits established by the 'laws of physics.' First, there is a limited amount of solar energy available to a plot of land of a unit area—the solar constant is about $1365\,\mathrm{W\,m^{-2}}$ and roughly one-half of that energy is absorbed by the Earth's surface (Trenberth et al. 2009). Consequently, this limited amount of energy constrains the amount of moisture and nutrients that plants and other life forms can extract from within a plot of land. Second, the assembly of leaves on a plant and plants across landscapes is a complex process that exhibits scale-emergent properties. In the long run, this condition causes the metabolism of a landscape to be invariant with the size of the individual organisms—a landscape will either sustain a lot of small individuals with relatively low specific (mass-based) metabolic rates or a few large individuals with relatively high specific metabolic rates (Enquist et al. 1998).

The state and fate of the climate and ecosystems are intrinsically linked by a complex network of fast and slow, positive and negative feedbacks (Field et al. 1995; Kleidon 2009; Lenton and van Oijen 2002). On hour to daily time scales, the state of the weather drives plant and microbial physiology, like photosynthesis, transpiration, and respiration by autotrophs and heterotrophs. In turn, these processes feedback onto the state of the atmosphere through water, heat, and carbon dioxide exchange (**Figure 1**). On daily to seasonal scales, the integration of these physiological processes determines the net amount of matter that is assimilated by vegetation and how it is allocated to leaves, stems, and roots. The structure and function of the ensuing population of plants establishes a number of biophysical properties. Leaf area index, for instance, modulates mass and energy exchange by affecting how much sunlight is absorbed and by serving as a source and sink for trace gases. The shedding of senescent leaves and eventual death of plants, on yearly to decadal time scales, feeds biogeochemical cycles that sustain the carbon and nutrient pools and processes like mineralization, nitrification, ammonification, and denitrification, which feedback and determine the physiological capacity of the plants. Dynamic ecosystem processes, like disturbance, competition, reproduction, and dispersal, determine 'who is where' and 'how many are there.' These dynamical ecosystem processes operate on decade to century time scales and affect the biophysical attributes of the ecosystem that regulate energy exchange by modulating the biogeochemical fluxes into and out of the system and soil properties. In addition, there is a feedback with soil formation, which depends on weather, life, topography, parent material, and time (Jenny 1994). In sum, the feedbacks illustrated in **Figure 1** contribute to the fact that the global distribution of biomes and soils and the structural, functional, and biophysical properties they possess are closely interrelated with climate (Holdridge 1947; Jenny 1994; Stephenson 1990). The feedbacks among these linked processes also account for how different biomes have shifted, expanded, or contracted during different climatic states in Earth's history (Prentice et al. 1992; Woodward and Lomas 2004).

The most critical biophysical properties that regulate the fluxes of energy and trace gases include leaf area index, albedo, photosynthetic capacity, surface conductance, and aerodynamic conductance (Alton 2011; Dickinson 1983; Masson et al. 2003). In turn, the laws of physics constrain the morphology and function of leaves and root systems. Through natural selection, plants have developed leaves with a complex combination of shapes, sizes, and functions (Wright et al. 2004) that optimize the mass and energy exchange for the climate and habitat in which they exist (Taylor et al. 1975); biophysical interactions have forced leaves to evolve that are small to large in size, with broad- or needle-shapes, evergreen or deciduous habits, and C_3, C_4, or CAM photosynthetic pathways. Below ground, roots may be fibrous or tap-rooted and their vertical distribution may be concentrated in shallow soil layers or possess a subpopulation of pioneers that seek water deep into the soil or far beyond the horizontal reach of the plant canopy (Jackson et al. 1996). In essence, natural selection forced the rooting network of plants to vary in shape, with the ultimate outcome being volume filling and optimizing pursuit of water and nutrients within the soil column (Niklas and Enquist 2001).

Predicting how these biophysical properties may change is complicated by the fact that some of these properties are plastic and will seasonally vary, like photosynthetic capacity (Wilson et al. 2001; Xu and Baldocchi 2003). On longer time scales, the

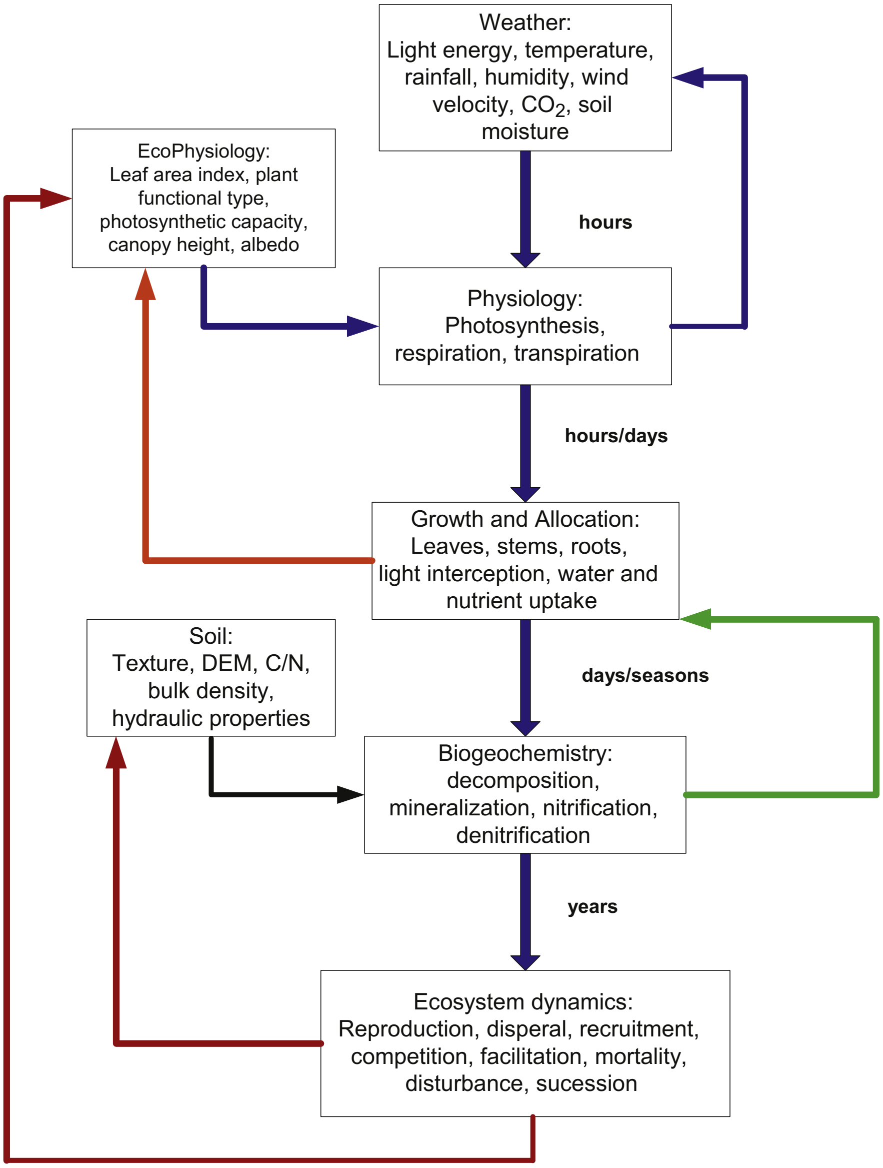
Weather:
Light energy, temperature, rainfall, humidity, wind velocity, CO_2, soil moisture
EcoPhysiology:
Leaf area index, plant functional type, photosynthetic capacity, canopy height, albedo
hours
Physiology:
Photosynthesis, respiration, transpiration
hours/days
Growth and Allocation:
Leaves, stems, roots, light interception, water and nutrient uptake
Soil:
Texture, DEM, C/N, bulk density, hydraulic properties
days/seasons
Biogeochemistry:
decomposition, mineralization, nitrification, denitrification
years
Ecosystem dynamics:
Reproduction, disperal, recruitment, competition, facilitation, mortality, disturbance, sucession

Figure 1 Fast and slow ecosystem processes that connect to mass and energy exchange, the biophysical properties of the ecosystem, and its feedback within the climate system.

temporal variation of a subset of biophysical properties may experience hysteresis; their properties will follow different temporal trajectories if the ecosystem is collapsing or recovering (Scheffer and Carpenter 2003; Suding et al. 2004); or the key biophysical properties may experience sudden switches if environmental stresses pushes an ecosystem into an alternative stable state (D'Odorico and Porporato 2004).

To assess how ecosystems regulate heat (temperature), water vapor, and carbon dioxide transfer into and out of the atmosphere, we start with the conservation of mass. It informs us that the time rate of change of energy, or trace gases, in the atmospheric reservoir is determined by the differences in fluxes entering or leaving the top and bottom of that reservoir. Metaphorically, one can envision the connection between the land–atmosphere fluxes and the atmospheric reservoir to how the level of water in a bath tub is determined, for example, by the balance, or imbalance, of the flows of water leaving the tap and entering the drain.

While the locus of energetic activity centers on the leaf and the cells of its mesophyll, the metabolism of the whole ecosystem is not as simple as adding up all of its parts and taking an average (Rastetter et al. 1992). To compute the metabolic activity of an ecosystem, one needs to integrate a set of nonlinear functions that experience non-Gaussian forcing by sunlight (Norman et al. 1981). One fraction of the leaves is sunlit. The amount of sunlight they receive depends on their angle relative to the sun (Ross 1976). But often, the sunlit leaves are exposed to light levels that saturate photosynthesis. The other fraction of leaves is shaded by those overhead. How much sunlight they receive depends on how deeply they are stacked in the canopy. These photosynthetic rates of the shaded leaves are highly sensitive to increases or decreases in sunlight. In principle, the arrangement of multiple leaf layers in a plant stand trap and scatter photons and modulates how much energy is absorbed or reflected (Dickinson 1983; Ross 1976). Ultimately, the amount of sunlight a vegetated canopy absorbs determines how warm the surface may get and how much water will be evaporated through transpiration (Jarvis and McNaughton 1986).

The radiative energy balance of a landscape is responsible for the thermal regime about organisms and ecosystems. Consideration of the net radiation balance is important because it provides the theoretical knobs that one may adjust to evaluate how energy exchange of ecosystems responds to changes in weather and climate, ecosystem structure, and plant physiology. The net radiation balance is defined as the algebraic sum of incoming solar shortwave radiation (R_{in}) minus outgoing, reflected, radiation (R_{out}) plus incoming terrestrial longwave radiation (L_{in}) minus terrestrial longwave energy that is radiated by the surface (L_{out}), which is in proportion to its absolute temperature to the fourth power. The net radiation (R_n) balance supplies the energy that drives sensible heat (H) and latent heat exchange (λE), conductive heat transfer in and out of the soil, and vegetation (G) and photosynthesis (P):

$$R_n = (1-\alpha)R_g + \varepsilon L_{\mathrm{in}} - \varepsilon\sigma T_s^4 = \lambda E + H + G + P \qquad (1)$$

The Penman–Monteith equation provides the guiding theory for examining how changes in surface properties of vegetation and ecosystems will alter latent heat exchange, the energy used to evaporate water (Monteith 1981). The Penman–Monteith equation is defined by the algebraic manipulation of the surface energy budget (eqn. 1), in conjunction with Ohm's law of resistance to model fluxes, and the linearization of several temperature-dependent functions like saturation vapor pressure and the emission of longwave energy—its derivation achieves the goal of replacing functions dependent on surface temperature with those dependent upon air temperature, a quantity that is readily measured at a weather station:

$$\lambda E = \frac{s(R_n - S) + \rho \cdot C_p \cdot G_H \cdot D}{s + \gamma + \gamma \dfrac{G_H}{G_s}} \qquad (2)$$

In eqn. 2, G_H is the boundary layer conductance for heat transfer ($\mathrm{m\,s^{-1}}$) and G_s is the surface conductance ($\mathrm{m\,s^{-1}}$); one can also pose this equation in terms of resistances, which are the reciprocals to conductance. Air density is denoted by ρ, specific heat of dry air is quantified by C_p, the psychrometric constant is γ, D is the vapor pressure deficit, and s is the slope of the saturation vapor pressure–temperature ($e_s(T)$) relation with respect to temperature. The slope of the saturation vapor pressure – temperature function, s, equals 145 $\mathrm{Pa\,{}^\circ C^{-1}}$ at 20 °C and it ranges between 32 and 473, as air temperature increases from -5 to 44 °C. Because $e_s(T)$ has a strong temperature dependence, a smaller fraction of available energy will be lost to latent heat exchange under cool climates than under warm climates. This effect reinforces dry desertlike conditions in the tundra and humid conditions in the tropics.

The aerodynamic conductance, G_H, is a function of surface roughness, friction velocity, and the thermal stratification of the atmosphere (Monteith and Unsworth 1990). Forests are aerodynamically rougher than short and smooth vegetation like crops and grasslands; the canopy conductance over a tall forest may be two to three times greater than that of adjacent grassland for a similar free-stream wind velocity. Hence, replacing tall vegetation with short vegetation reduces the fraction of available energy that is partitioned into latent heat exchange (Raupach 1995, 1998) and vice versa.

The surface conductance (G_s) connotes ecological and physiological information onto the Penman–Monteith equation (Jarvis 1976). In practice, this conductance is a function of leaf area index, soil moisture, plant functional type, and nutrient content of the leaves (Baldocchi and Meyers 1998; Kelliher et al. 1995; Schulze et al. 1994). A closed canopy comprised of well-watered fertilized C_3 plants will possess a higher conductance than a canopy with well-watered fertilized C_4 plants. Also, these plants will exert a higher conductance to vapor exchange than plant canopies that are open or experience stress due to soil moisture deficits or limited nutrients.

The leaf area index of native plant stands are either limited by water or light. Dense canopies with high leaf area indices ($\mathrm{LAI} > 3$) are able to form where rainfall is great and it exceeds evaporation. Conversely, sparse canopies form where rainfall is sparse or where potential evaporation far exceeds rainfall (Baldocchi and Meyers 1998; Grier and Running 1977; Sankaran et al. 2005).

The vapor pressure deficit that drives evaporation in the Penman–Monteith equation is not a passive variable. It depends on the depth of the planetary boundary layer and the fluxes of moisture into the bottom and top of that volume. The depth of planetary boundary layer, its rate of growth, and how much dry and moist air it may entrain from above are functions of the amount of sensible heat injected into the lower boundary layer (Jacobs and Debruin 1992; McNaughton and Spriggs 1986). In theory, the growth of the planetary boundary layer is a function of the virtual sensible heat flux and the gradient of potential temperature across the entrainment layer. When the growth of the planetary boundary layer intersects with the lifted condensation level, there is a chance for condensation and clouds to form, increasing the probability of precipitation (Siqueira et al. 2009) and reducing the amount of solar radiation at the Earth's surface.

4.08.3 Sensitivity to Environmental Stress

How well ecosystems may continue to serve the climate and the atmosphere depends on how they will respond to secular trends in a suite of environmental drivers that are associated with the emerging geological epoch, the Anthropocene (Steffen et al. 2007). Ongoing changes in the atmospheric environment—rising levels in carbon dioxide, temperature, nitrogen deposition, land management practices, atmospheric pollution, and variable changes in rainfall—are expected to impose both negative and positive effects on the metabolic activity of ecosystems that are direct and indirect (Field et al. 1995; Korner 2006). How well ecosystems respond to this suite of environmental changes depends upon their ability to tolerate, avoid, acclimate, and/or shift their domain—the alternative is death or extinction. Their response will also depend on antecedent conditions, if the changes are gradual or fast, and whether extreme events occur that cross certain thresholds (Porter and Semenov 2005).

While this chapter focuses on vulnerability of ecosystem energy, and trace gas, exchange to climate, we also cannot ignore human-induced land use change as it is an agent of the new Anthropocene epoch (Steffen et al. 2007). Land use change is occurring through deforestation, afforestation, fire, disease, successional ecosystem dynamics, and invasive species and is covarying with climate (Kabat et al. 2004). Because land use change affects the composition of the ecosystems and the biophysical properties they possess, land use change may have an immediate and stronger impact on the regulatory services that ecosystems provide through trace gas and energy exchange than climate change, *per se* (Bounoua et al. 2002; Diffenbaugh 2009; Kabat et al. 2004; Levis 2010; Pongratz et al. 2009; Snyder et al. 2002).

In the following three subsections we discuss general insights on how mass and energy responds to environmental change drawing on information from extensive and long-term field studies, feedback theory, and comprehensive modeling exercises.

4.08.3.1 Lessons from Field Observations

A community of micrometeorologists and ecologists are studying how sensitive mass and energy exchange may be to a variety of climate, weather, and ecological forcing through a global network of long-term flux studies (Baldocchi 2008; Baldocchi et al. 2001). Studies exceeding a decade in length are proving noteworthy in understanding how mass and energy exchange at individual sites may vary with year-to-year modulation in sunlight, temperature, and rainfall (Granier et al. 2008; Grunwald and Bernhofer 2007; Ilvesniemi et al. 2010; Pilegaard et al. 2011; Urbanski et al. 2007; Zha et al. 2010). These long-term studies are also adept at determining how mass and energy exchange of various ecosystems respond to stressful conditions like drought, heat-spells, and freezes (Granier et al. 2007; Gu et al. 2008; Reichstein et al. 2007b; Rotenberg and Yakir 2010; Teuling et al. 2010; Zha et al. 2010).

The European 2003 heat-spell and drought has proven to be an excellent test case on how ecosystem carbon and water exchange vary with warming and drying (Granier et al. 2007; Reichstein et al. 2007b; Teuling et al. 2010). Initially, more sensible heat was lost by the regional forests than grasslands, as forests were optically darker and exhibited greater stomatal control on gas exchange. As the drought prolonged, the grasslands with shallow root systems depleted their soil moisture reserve. This forced the grasslands to become warmer than the forests and accelerated the heat-spell across Europe. Hence, grasslands were more vulnerable to drought than surrounding forests. With respect to variation within forest types, beech and broadleaved Mediterranean forests were found to be more sensitive to the drought and heat-spell than spruce and pine forests (Granier et al. 2007).

Studies across ecological or climatic gradients reveal how mass and energy exchange responds to leaf area, rain, temperature, and sunlight (Reichstein et al. 2007a; van Dijk et al. 2005; Yi et al. 2010), CO_2 and N deposition (Magnani et al. 2007), or varied plant functional types (Anderson-Teixeira et al. 2011; Baldocchi et al. 2000, 2010). Long-term studies of contrasting pairs, or clusters, of sites allow investigators to study how a change in land surface properties affect mass and energy exchange of natural ecosystems. A condensed survey reveals published studies have compared mass and energy exchange of (1) savanna versus grasslands (Baldocchi et al. 2004; Scott 2010), (2) deciduous versus evergreen broadleaved forests (Baldocchi et al. 2010), (3) deciduous broadleaved forest versus evergreen conifer forests (Baldocchi et al. 2000; Eugster et al. 2000; Zhang et al. 2001), (4) boreal forests versus grasslands (Zha et al. 2010), and (5) conifer forests versus desert (Rotenberg and Yakir 2011). Another body of literature studies the effects of disturbances, like fire, logging, deforestation, and insect infestation, on mass and energy exchange using a network of sites distributed across a chronosequence (Amiro et al. 2006a; Anderson-Teixeira et al. 2011; Brown et al. 2010; Liu and Randerson 2008; Montes-Helu et al. 2009) or natural regeneration (Juang et al. 2007; Lohila et al. 2010; Stoy et al. 2006).

The replacement of semi-arid woodlands with grass and shrubs yields some counterintuitive findings on mass and energy exchange worth discussing. Woody vegetation is darker than surrounding shrub and grasslands, causing savannas and pine forests to absorb much more solar energy (Baldocchi et al. 2004; Montes-Helu et al. 2009; Rotenberg and Yakir 2011). But more effective convective heat loss and evaporative cooling cause aerodynamically rough forests to experience lower surface temperatures than contrasting smoother landscapes.

In order to synthesize the information contained in the cited papers, we extract information on annual sums of energy fluxes for broad climate zones and plant functional types of interest (Table 1); these data are from a global network of long-term carbon, water, and energy flux measurements, FLUXNET (Baldocchi et al. 2001). The amount of incident solar radiation (R_g) ranges between about 3.4 and 6 GJ m^{-2} y^{-1}. Lowest values of solar energy inputs are associated with northern ecosystems, like wetlands and boreal forests, and the greatest values associated with subtropical semi-arid ecosystems, like savanna. Intermediate levels of solar radiation are received by ecosystems in humid tropical regions because skies are often cloudy. Ecosystems with the most net radiation (R_n) do not correspond with regions receiving the most sunlight. Evergreen broadleaved forests are optically dark so they retain a relative high fraction of ample incident sunlight. Conversely, grasslands and wetlands in northerly temperate and boreal climates are reflective and retain the least.

Distinct plant functional types (forest, grasslands, shrublands) in different climates (tropical, temperate, boreal) use their available energy differently. Regarding the amount of net radiation used to drive latent heat exchange (λE) over the course of a year, the highest fraction, on average, is associated with grasslands (65%) and the least is associated with evergreen needle-leaved forests (42%). The lowest fraction of net radiation that is consumed by sensible heat (H) is associated with crops (23%) and the largest fraction is associated with savanna woodlands (44%). Solar energy and its partitioning into sensible and latent heat exchange are poorly correlated with net ecosystem carbon exchange (NEE) at annual time scales. This occurs because NEE represents the difference between offsetting fluxes from two different pools (vegetation and soil) that are controlled by different factors.

So far, we have discussed many of the direct effects of ecosystems on energy and trace gas exchange. There are many conditional and indirect effects that play pivotal roles in how mass and energy exchange respond to climate conditions and

Table 1 Average sums of energy (global radiation (R_g), net radiation (R_n), sensible heat (H), latent heat (λE) fluxes, albedo, surface conductance (G_s), and net ecosystem carbon exchange (NEE)) for representative vegetation groups

	R_g $GJ\ m^{-2}\ y^{-1}$	R_n $GJ\ m^{-2}\ y^{-1}$	*Albedo* –	H $GJ\ m^{-2}\ y^{-1}$	LE $GJ\ m^{-2}\ y^{-1}$	G_s $mmol\ m^{-2}\ s^{-1}$	*NEE* $gC\ m^{-2}\ y^{-1}$
Crop	4.375	2.063	0.156	0.478	1.217	510	–237
Std. dev.	1.051	0.678		0.296	0.433	205	182
Grassland	4.707	1.6866	0.239	0.632	1.097	437	–156
Std. dev.	1.11	1.17		0.478	0.413	224	171
Wetland	3.427	1.3279	0.240	0.359	0.725	454	–107
Std. dev.	0.818	0.574		0.208	0.421	159	123
Evergreen needle-leaved forest	4.046	2.242	0.106	0.891	0.954	432	–247
Std. dev.	0.988	0.952		0.477	0.456	173	331
Evergreen broadleaved forest	5.216	3.289	0.0825	0.893	1.888	672	–381
Std. dev.	0.909	0.963		0.329	0.899	456	331
Deciduous broadleaved forest	4.086	2.310	0.204	0.651	1.081	497	–403
Std. dev.	1.000	0.664		0.372	0.4659	196	289
Savanna	6.058	2.93	0.121	1.304	1.388	355	–136
Std. dev.	1.605	1.543		0.507	0.920	240	166

The data were extracted from annual sums from the FLUXNET database, www.fluxdata.org

land use. Important conditional factors include the length of the growing season, presence and absence of snow, the extent of the dry and wet season, soil fertility, and time since disturbance.

Time since disturbance has a noteworthy impact on mass and energy exchange, as determined from chronosequence studies. In the boreal forest, for example, albedo and the fraction of net radiation that was consumed as latent heat decreased in a nonlinear function with time since disturbance (Amiro et al. 2006b). What does this information tell us about reforestation or deforestation? Until recently, it was conventional wisdom that forests evaporated more water than grasslands under similar conditions causing runoff and water yield to be greater from woodlands that were cut and replaced by grass. New information, from a 30-year record of a gauged watershed in Wales, has changed this perception. The investigators found that forest evaporation decreased with stand age to the extent that the forest now evaporates as much or less than a neighboring grassland (Marc and Robinson 2007).

Another indirect factor of interest is biodiversity. An initial inspection of the FLUXNET database found that an increase in the number of dominant deciduous tree species reduced the fraction of absorbed energy that is lost as latent heat (Baldocchi 2005). It was hypothesized that the hydraulic conductivity of a mixed forest stand is less than a less diverse forest. Yet, reinspection of this hypothesis with a longer and more extensive dataset finds no significant relation between annual evaporation and the number of dominant species across a spectrum of deciduous broadleaved forests (Figure 2). Theoretically, evaporation is modulated by the way plants of different traits assemble to affect the leaf area index and stomatal conductance of a landscape (Jarvis and McNaughton 1986), rather than number of species, *per se*.

4.08.3.2 Lessons from Feedback Theory

Many positive and negative feedbacks act upon energy and trace gas exchange and connect ecosystems and the atmosphere (Brubaker and Entekhabi 1996; Field et al. 1995; Jacobs and Debruin 1992; McNaughton and Jarvis 1991; van Heerwaarden et al. 2009). In the following, we will discuss feedbacks that control surface temperature and soil moisture because they establish the respective gradients against which heat and moisture are lost from an ecosystem and transferred to the atmosphere.

To quantify the positive and negative feedbacks that conspire to increase or decrease surface temperature, it is best to examine them through the lens of the surface energy balance and its coupling to the planetary boundary layer (Figure 3); in this figure, the term in each box is assumed to experience a positive increase; the sign and color of the arrow that follows defines whether the linked process increases (+, red) or decreases (−, blue) (Harte 2001).

An increase in surface temperature would initiate three parallel feedback loops. One loop would increase sensible heat exchange (H). A second loop increases the amount of longwave energy lost by the surface, causing a reduction in the net

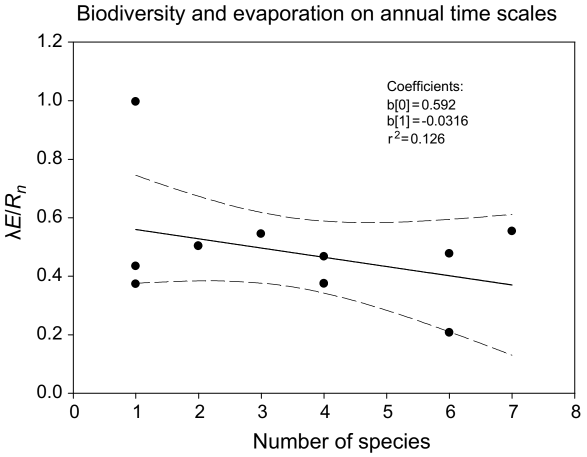

Figure 2 Correlation between number of dominant overstory tree species and annual evaporation. We evaluated evaporation in terms of latent heat exchange and normalized it by the net radiation budget of the plant stand. This analysis is based on data from the FLUXNET database at www.fluxdata.org. The slope is not different from zero at the 5% probability level ($P = 0.256$).

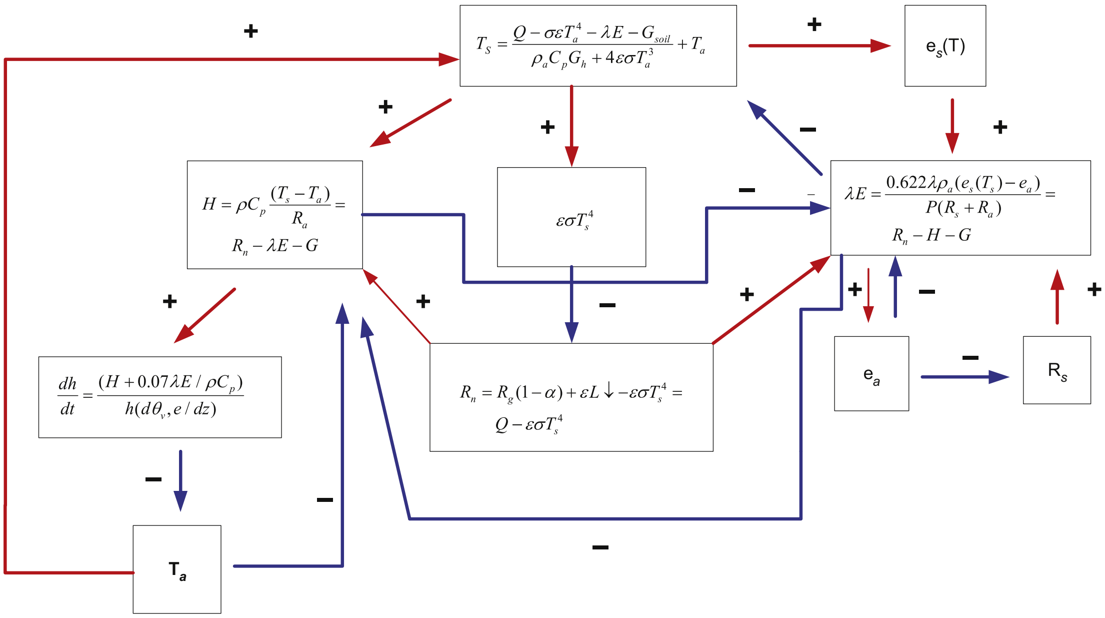
$T_S = \frac{Q - \sigma\varepsilon T_a^4 - \lambda E - G_{soil}}{\rho_a C_p G_h + 4\varepsilon\sigma T_a^3} + T_a$
$e_s(T)$
$H = \rho C_p \frac{(T_s - T_a)}{R_a} =$
$R_n - \lambda E - G$
$\varepsilon\sigma T_s^4$
$\lambda E = \frac{0.622\lambda\rho_a(e_s(T_s) - e_a)}{P(R_s + R_a)} =$
$R_n - H - G$
$\frac{dh}{dt} = \frac{(H + 0.07\lambda E / \rho C_p)}{h(d\theta_v, e/dz)}$
$R_n = R_g(1-\alpha) + \varepsilon L\downarrow - \varepsilon\sigma T_s^4 =$
$Q - \varepsilon\sigma T_s^4$
e_a
R_s
T_a

Figure 3 Feedback loops associated with surface temperature (T_s) through the interactions between the surface energy balance, the state of the atmosphere (humidity and temperature), growth of the planetary boundary layer, and the physiological status of the vegetation. Undefined terms include air density (ρ), vapor pressure (e_a), global radiation (R_g), albedo (α), incoming longwave energy (L_{in}), emissivity (ϵ), the Stefan–Boltzmann constant (σ), specific heat capacity (C_p), pressure (P), latent heat of evaporation (λ), soil heat flux (G), aerodynamic resistance (R_a), and potential virtual temperature (θ_v).

radiation balance (R_n). A third loop would increase the saturation vapor pressure of the surface (e_s). The first loop leads to an increase in the height of the planetary boundary layer (h), thereby entraining warm dry air from above the inversion of the planetary boundary layer. This sequence can promote evaporation by maintaining a strong gradient in humidity between the moist surface and the drier bulk atmosphere. The second loop decreases the amount of net radiation (R_n) that is available to drive sensible and latent heat exchange. The third loop increases the humidity gradient between the surface and free atmosphere that promotes evaporation (E) via latent heat exchange (λE). It also promotes an internal feedback loop by humidifying the boundary layer and decreasing stomatal resistance (R_s). These actions promote latent heat exchange, whose evaporative cooling retards surface temperature perturbations. Overall, the three feedback loops shown in Figure 3 interact to force a negative feedback on surface temperature. This leads to stabilization in surface temperature and helps explain why the mean growing-season surface temperature of plants from across the globe converge on a seasonally-weighted temperature near 21 °C (Helliker and Richter 2008).

The feedback loops illustrated in Figure 3 are fast feedbacks. This figure does not consider slower changes that would be associated with albedo and surface resistance as the functional type of vegetation and its leaf area change on slower ecological time scales (Chapin et al. 2008). Nor does Figure 3 consider the effects of snow or the presence or absence of reflective clouds, which may suppress or promote rainfall, change soil moisture, and alter leaf area index; removing forests, for example, will inhibit transpiration, which feeds the production of clouds and rain, which provide sufficient moisture to sustain forest vegetation (Anderson et al. 2011; Jackson et al. 2008).

To consider the slower feedbacks associated with soil moisture and canopy cover, we need to consider the interactions between evaporation, cloud generation, the solar radiation budget, rainfall, and leaf area index (Brubaker and Entekhabi 1996; D'Odorico and Porporato 2004; Koster et al. 2004). Figure 4 shows how moist soils promote evaporation, which humidifies the atmosphere and reinforces rainfall and soil moisture; ultimately, evaporation from moist ecosystems is limited by solar radiation (Budyko 1974; Donohue et al. 2007). Conversely, dry soils promote dry conditions and warm temperatures because the lack of evaporation inhibits evaporative cooling at the surface and a source of moisture for cloud formation and precipitation. The feedbacks associated with soil moisture are slower than those associated with surface temperature and can persist for weeks and months. The soil moisture feedbacks are most dominant at transitional 'Goldilock' regions that are neither too moist or dry, like the Great Plains of North America, the Sahel of Africa, and the Indian subcontinent (Koster et al. 2004; Seneviratne et al. 2006). There, they can set up alternative stable states of wet or dry conditions, initiated by spring climate anomalies (D'Odorico and Porporato 2004) or vegetation patterns (D'Odorico et al. 2007). On the other hand, the soil moisture-precipitation feedback may be stymied in situations where moisture advects across the landscape from nearby oceans, like the Gulf of Mexico or the Pacific Ocean.

On decadal time scales, we have to consider how these feedbacks modulate LAI and vegetation patterns (Baldocchi and Meyers 1998; Bounoua et al. 1999; D'Odorico et al. 2007; Donohue et al. 2007). On century to millennial time scales, another set of feedbacks come into play. They involve atmospheric circulation and help explain energy balance-land surface feedbacks for the Sahara desert (Charney et al. 1975) and Arctic

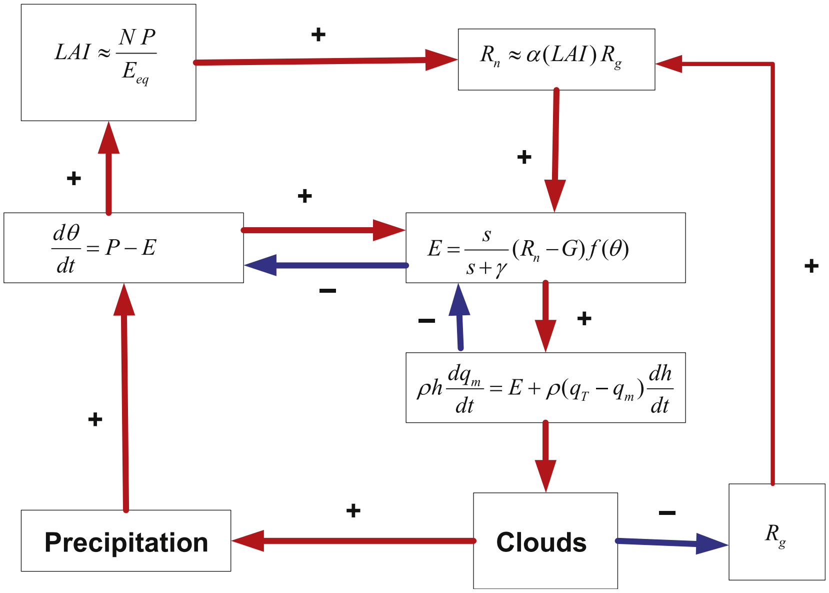
$LAI \approx \frac{NP}{E_{eq}}$
$R_n \approx \alpha(LAI)R_g$
$\frac{d\theta}{dt} = P - E$
$E = \frac{s}{s+\gamma}(R_n - G)f(\theta)$
$\rho h \frac{dq_m}{dt} = E + \rho(q_T - q_m)\frac{dh}{dt}$
Precipitation
Clouds
R_g
+
−

Figure 4 Feedback loop between precipitation (P), evaporation (E), solar radiation (R_g), LAI, and volumetric soil moisture (θ). These fluxes will interact to alter height of the boundary layer (h) and the humidity mixing ratio in the mixed layer (q_m). Other terms include air density (ρ), slope of the saturation vapor pressure–temperature function (s), the psychrometric constant (γ), humidity mixing ratio of the troposphere (q_T), and soil heat flux (G).

(Swann et al. 2010). An explanation for the persistence of the Sahara desert starts with the high albedo and warm surface temperature of this dry region with no vegetation. Together, these two facts reduce the net radiation balance of the surface despite its sunny locale. A regionally deficit radiation balance imposes a large-scale sinking action on the atmosphere, which reduces the relative humidity and inhibits convective action and precipitation. These links force a negative feedback on vegetation and albedo. In the Arctic, an expansion of the tree line would darken the albedo of the present tundra and could provide a new source of water vapor to the atmosphere through enhanced transpiration. This extra source of water would presumably expand over the ocean, warm it, melt the ice pack, and darken the ocean further. Together, these linked processes would further warm the land and reinforcing the feedback for more productivity by trees, lower albedo, and more transpiration.

4.08.3.3 Lessons from Comprehensive Land–Atmosphere Interaction Models

Biophysical models have the potential to tease apart the interactive effects of temperature and CO_2 and precipitation and land cover on current trends in climate. In practice, biophysical models can turn on or off processes that control energy exchange and compute how climate conditions may evolve (Bounoua et al. 1999; Brovkin et al. 2009; Claussen 1998; Dekker et al. 2010; Jacobs and Debruin 1992; Kleidon et al. 2000; Seneviratne et al. 2010; van Heerwaarden et al. 2010). For example, they can consider changes in a suite of biophysical variables (albedo, energy partitioning, and surface roughness) and biogeochemical and ecological processes (down regulation of photosynthesis and stomatal conductance, increased plant growth, and water use efficiency).

The simplest experiment is to consider a world with and without vegetation. Shukla and Mintz (1982) were among the first global modelers to demonstrate the role of evaporation from vegetation on the global fields of clouds, rainfall, temperature, and vertical motion using a coarse grid (four degree) model. Kleidon et al. (2000) performed a numerical experiment that considered a ‘green world’ versus a ‘desert world.’ They found that the presence of vegetation causes land evaporation to triple and this evaporative cooling reduces air temperature by 8 K, which reduces thermal radiation loss and increases the net radiation budget. Experiments like the green versus desert worlds set the upper limit on what to expect in how the climate may change with the state and extent of vegetation. In practice, land use change will exert its influence most greatly at regional and at smaller spatial scales, because 70% of the Earth’s surface is ocean. There is also the issue that atmospheric–ocean circulation changes, rather than a global average surface temperature, would have a greater impact on the state and extent of vegetation.

In the case of a ‘green world,’ the type of vegetation that is present or is replaced will have different effects on the climate system. In general, changing the type of vegetation indeed has smaller impacts on climate than removing vegetation altogether. Brovkin et al. (2009) recently assume the vegetation of the world to be either forests or grasses. They found that the climate warmed by 0.7 K if the vegetation was forested and it declined by 0.6 K if it was grass. In earlier work, Brovkin et al. (2004) reported that a biogeophysical mechanism that corresponded with changes in land cover caused global air temperature to decrease by 0.26 K. Conversely, biogeochemical processes forced the climate to warm by 0.18 K.

In another study, Bounoua et al. (2002) found land use change to have a greater impact on regional climate than on global climate. They reported that converting large swaths of forests and grasslands to crops cooled surface temperatures by 0.7 K during the summer and by 1.1 K during the winter. Conversely, converting tropical forests to C_4 grasslands warmed surface temperature by 0.8 K because C_4 grasses impose greater stomatal control on transpiration than C_3 grasses and trees. For a global average, they found temperate cooling was offset by tropical warming.

4.08.4 What Are Current Trends in Climate-Induced Changes in Mass and Energy Exchange?

Global warming is expected to accelerate the hydrological cycle and increase the rate of land evaporation. This expectation has led to a paradox in the observational record that is revealing a multidecadal trend in decreasing pan evaporation (Liu et al. 2004; Peterson et al. 1995; Roderick and Farquhar 2002). At present, three competing and/or complementary hypotheses are being debated to explain this phenomenon (van Heerwaarden et al. 2010). The first hypothesis revolves around the idea that the secular trend in decreasing pan evaporation reflects a moistening of the atmosphere by an increase in actual land evaporation (Brutsaert and Parlange 1998). The second hypothesis revolves around the consequence of global dimming (Stanhill and Cohen 2001) and its impact on the energy available to drive evaporation (Liu et al. 2004; Roderick and Farquhar 2002). This hypothesis is strongest in humid regions where evaporation in energy limited *a priori*, and is thereby sensitive to additional reductions in solar energy. The third hypothesis claims an association with a global stilling of the winds (Roderick et al. 2007). Most recently, van Heerwaarden et al. (2010) used a coupled energy balance/planetary boundary layer model to investigate this problem. They found that an increase in soil moisture leads to more actual evaporation and less pan evaporation under all conditions through feedbacks associated with evaporation and vapor pressure deficit and near surface temperature. On the other hand, increasing trends in continental-scale river runoff have been reported and they are attributed to a reduction in transpiration due to elevated CO_2 (Gedney et al. 2006).

The more difficult task is evaluating the low probability, high impact indirect responses to climate extremes that might cause major shifts in the landscape and its biophysical properties. These indirect effects operate on slow time scales, so their effect may not be obvious at first glance (Dekker et al. 2010). They have the potential to change an ecosystem from one stable state to another (Rietkerk et al. 2004). So they should not be ignored.

Removing keystone species or introducing an invasive species has the potential to disrupt the functioning of an ecosystem and change its composition, which in turn can affect biophysical forcings on the weather and climate. Prominent examples are insect outbreaks that defoliate wide swaths of forests (Brown et al. 2010), the defoliation of vegetation along the ‘bunny fence’ in Australia (Lyons et al. 1993), the exclusion or introduction of grazing (Allard et al. 2007; Bremer et al. 2001), and the occurrence or suppression of fire (Amiro et al. 2006b; Montes-Helu et al. 2009).

If future ecosystems experience warmer and drier conditions, an increase in fire frequency and severity may be in their future (Westerling et al. 2006). Looking at the energy balance across a chronosequence of burned sites, the general finding is that burnt sites are brighter than the forests they replace, reducing net radiation (Amiro et al. 2006b; Liu and Randerson 2008). With less available energy comes a reduction in sensible and latent heat exchange.

How vulnerable mass and energy exchange may be to climate-induced stresses may depend upon its successional stage—the late Eugene. Odum (1969) hypothesized that an ecosystem would be less vulnerable to environmental stresses as one proceeds along a successional sequence. Stoy and colleagues (2008) tested this hypothesis by measuring mass and energy fluxes over an abandoned field, an intermediate-aged pine forest, and an old hardwood forest. They found that the abandoned field was more susceptible to year-to-year variations in weather than the more established hardwood forest; the abandon field experienced the greatest year-to-year variation in evaporation; the pine stand fell in between. In a companion study, Juang et al. (2007) reported that differences in albedo caused the brighter grass field to be 0.9 K cooler than the pine forest and 0.7 K cooler than the hardwood forest. These radiative effects were smaller in magnitude and opposite in sign from the energy balance forcings associated with ecophysiology and aerodynamics. These factors cause the grass field to be +2 K warmer than the nearby forests. In support of the findings of Stoy et al., my group found that year-to-year differences in water (±86 mm) and carbon exchange ($\pm 113\,\mathrm{gC\,m^{-2}\,y^{-1}}$) of an annual grassland were much greater than the water (±61 mm) and carbon exchange ($\pm 46\,\mathrm{gC\,m^{-2}\,y^{-1}}$) of an adjacent oak savanna woodland with investment in deep roots (Ma et al. 2007; Ryu et al. 2008). Most recently, Zha et al. (2010) reported that annual evaporation was higher and more variable for a boreal aspen forest (405 ± 84 mm, mean ± standard deviation (s.d.)) and grassland (395 ± 90 mm), which are transitional ecosystems, than the black spruce (374 ± 34 mm) and jack pine (300 ± 20 mm) forests that approach climax states.

4.08.5 Policy/Stakeholder Recommendations

A number of lessons have been learned about mass and energy exchange of ecosystems and their vulnerability to climate that may have implications on policy and stakeholder decisions. First, there are no simple black–white answers. For example, we have learned that mass and energy exchange are associated with many positive and negative feedbacks that operate across a continuum of fast to slow time scales. This attribute buffers complex systems, like ecosystems, to many external perturbations, but it also makes them vulnerable to abrupt change if thresholds are exceeded. Also, complexity may make the response of ecosystems to environmental forcings susceptible to hysteresis—the functional response of the system depends on whether the forcing variable is increasing or decreasing.

Gertrude Stein is credited for stating ‘rose is a rose.’ We cannot take such poetic license and presume ‘a forest is a forest’ such that energy exchange from similar vegetation types is the same across regions, continents, or the globe. One evolving theme in the literature is how the mass and energy exchange of a forest system changes with time since disturbance, as does its vulnerability to climate perturbations. Together, this information must cause us to rethink how reforestation or deforestation may change the water balance of a region (Marc and Robinson 2007).

This said, the principles discussed in this paper give the ecological engineer 'knobs to turn' and information on how sensitive those knobs may be. In practice, many of the responses of mass and energy exchange to climate perturbations are conditional upon plant functional type, antecedent conditions, and climate statistics such as seasonal high and low extremes, rather than mean annual climate forcings. Tuning some 'knobs' of the energy balance will force immediate changes and other slow ones, like the position of biomes and the composition and properties of their vegetation if the climate where they occur changes (Jackson and Overpeck 2000). So, the pace of any change in long-term regional and local climate statistics would have a major impact on how well biomes shift, adjust, or adapt. In addition, the literature is clear on showing that weather can get locked into a behavior that may reinforce anomalous wet or dry conditions at regional scales, depending on antecedent condition. With positive feedbacks, the severity of these events can become quite intense like the 2003 European heat-spell, the 2010 Russian heat-spell, the Texas heat wave of 2011, and the floods that ravaged the Central United States during 2011.

Finally, ecosystems serve multiple purposes, which may have opposing effects. Hence, if we chose to engineer ecosystems for the benefit of the climate system, we have to be conscious of unintended consequences of our actions to manage and engineer landscapes to reduce ecosystem and climate vulnerability. For example, managing a landscape for sequestering carbon may lead to negative climate or air chemistry effects. For example, wetlands and forests are very effective carbon sinks. But the nature of flooding land will produce methane and nitrous oxides, which are powerful greenhouse gases.

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4.09 Carbon Storage in Terrestrial Ecosystems

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4.09.1 The Climate Regulation Ecosystem Service

The Millennium Ecosystem Assessment (2003) proposed a classification framework for ecosystem services, which has four top-level classes: provisioning services, which are tangible goods and typically have well-defined markets; cultural services, based on aesthetic or amenity value, which also often have markets; regulating services, which stabilize the supply of either of the above, or in other cases reduce the risk of natural disasters; and supporting services, which are ecological processes without which none of the above would occur, but which are not themselves directly used by people. The latter two service classes seldom have existing markets.

The 'climate service' provided by ecosystems – in other words, their contribution to ensuring that the climate of a given area is within certain desired bounds – is usually classified as regulating service. A substantial part, but by no means all, of this service is related to the ability of ecosystems to take up carbon dioxide from the atmosphere. With the creation of tradable carbon credits – formally through the Kyoto Protocol, and whatever treaties may succeed it, and informally through a variety of 'voluntary' schemes – ecosystem carbon uptake and storage has effectively become a provisioning rather than a regulating service. Just like other provisioning services, it is a physical quantity with a market and a price. Land stewards can choose to manage their land to include carbon storage as one of the commodities it provides.

At the global scale, it is easy to demonstrate that terrestrial ecosystems provide a large and crucial climate service. Life exists on this planet because of the particular atmosphere that is present here. The composition of the atmosphere is dependent on the organisms and ecosystems that have coevolved with the atmosphere over a period of many billions of years. Without this biota, the temperature, rainfall, and atmospheric circumstances on Earth would be very different, and not able to support human life. Thus the 'total value' of the climate regulating services is infinite. The more useful (and difficult) question is what is the value of a marginal change in the climate service, for a subset of the planet of perhaps just a few hectares? Can this service be relied on in the future?

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Specifically, is carbon storage biophysically dependable, against a backdrop of the substantial variability in the preindustrial climate of the Holocene, and the nonsteady state nature of the current perturbation of the global carbon cycle (National Research Council 2005)?

4.09.1.1 Mechanisms Delivering the Climate Service

The land surface modulates the climate in many different ways and at many scales. People have understood the microclimatic ameliorating effects of vegetation for centuries. It is the underlying principle of windbreaks, shade trees, and gardens. These effects are provided by slowing the wind, raising the humidity, intercepting solar radiation, and partitioning absorbed solar radiation into latent energy of evaporation rather than heat. The vegetated surface also helps to buffer humans from the consequences of climate extremes such as droughts, floods, or windstorms. These are all important parts of the 'climate service'. The focus of this chapter, however, is at a larger scale the role of the terrestrial surface in mitigating human-induced global change, specifically by acting as a sink for carbon dioxide, but also through non-CO_2 mechanisms (McAlpine et al. 2010). The climate system is never in a steady state, either interannually (e.g., Elis et al. 1978), or on longer timescales (Rial et al. 2004). The contemporary Earth climate system has, in addition, a significant human influence (National Research Council 2005). It is adjusting to a human-caused perturbation including the total emission of about $11\ \mathrm{Pg\,C\,year^{-1}}$ as carbon dioxide, $582\ \mathrm{Tg\,CH_4\,year^{-1}}$ as methane, $17.7\ \mathrm{Tg\,N\,year^{-1}}$ as nitrous oxide, and an average $19\,185\ \mathrm{Tg\,year^{-1}}$ of aerosols into the atmosphere (Solomon et al. 2007). These emissions are largely from the burning of fossil fuels, and with a significant additional component resulting from human-induced land cover change. Globally ecosystems absorb around half of the human-caused CO_2 perturbation, more or less evenly between the ocean and land (Prentice et al. 2001; Houghton 2003). The land uptake constitutes what is known as the 'terrestrial carbon sink'. It varies substantially in magnitude from year to year, much more so than the oceanic sink (Canadell et al. 2007; Rowhani et al. 2011). Inversion studies and *in situ* observations confirm that the terrestrial sink is widely distributed over the Earth's surface, though not evenly so (Gurney et al. 2004; Phillips et al. 1998). In addition, the pervasive human-induced changes in the land surface directly modify the climate through altering the surface fluxes of heat and water vapor.

This chapter focuses on the carbon storage aspect of climate on land. There is no general agreement on the relative contribution of the several processes thought to underlie the terrestrial carbon sink (Scholes et al. 1999). It is observed that when plants are exposed to higher levels of CO_2, their rate of carbon assimilation increases – a phenomenon known as CO_2 fertilization (Lobell and Field 2008). Many parts of the world are simultaneously experiencing N fertilization, either deliberately or as an unintended consequence of air pollution, which also increases production (Reay et al. 2008). Thirdly, large parts of Europe and North America are undergoing forest regrowth following clearing in past centuries – thus in the present time they act as carbon sinks (Nabuurs et al. 2003; Goward et al. 2008). A transient sink inevitably arises when a series of slow-turnover pools must be filled before respiration fluxes catch up with photosynthetic fluxes, trees must grow, die, and then decompose.

In addition to CO_2, several other radioactively active gases and particles produced or absorbed by the land surface also participate in the present imbalance in the global energy budget. The main ones are methane and nitrous dioxide, but carbon monoxide, a range of nonmethane hydrocarbons, and oxides of nitrogen contribute indirectly as precursors to tropospheric ozone, which is a powerful, but short-lived greenhouse gas. Organic aerosols and soot particles affect the radiation balance directly or indirectly by acting as cloud condensation nuclei. Change in the properties of the surface itself, especially its reflectance (known as albedo), alters the energy absorbed by the surface. For instance, when a bright surface such as snow is replaced by a dark surface such as a conifer canopy, the net result is warming (Betts 2000). There are other circumstances, such as the conversion of southwest Australian bushlands to agriculture, which could produce a cooling effect (Nair et al. 2007). 'Carbon', which has come to be used as shorthand for 'carbon dioxide', has tended to overshadow these other gases and processes, but this is a misleading simplification. Although CO_2 has the largest single direct human radiative forcing effect globally, in particular circumstances the other mechanisms are significant, even to the extent of overwhelming the carbon effect locally (e.g., Avila et al. 2012). If a net benefit to the climate system is the objective, rather than simply selling carbon into an undiscerning market, all the main known effects must be checked to ensure that the important ones have been taken into account under any given circumstance. It is perfectly feasible for an ecosystem to show an increase in carbon, but have a net detrimental effect on climate suitability for human purposes.

4.09.1.2 Pools and Fluxes

Carbon held within the ecosystem as a stock (also known as a 'pool', and having the general units of $\mathrm{g\,m^{-2}}$) has little direct effect on the climate as long as the total magnitude of that stock does not change. What causes a change in the global atmospheric concentration, and thus the climate, is a net flux of CO_2 out of the atmosphere and into the terrestrial ecosystem stock, or vice versa. Fluxes have units of $\mathrm{g\,m^{-2}\,year^{-1}}$; in other words they are rates. The confusion arises because fluxes are often measured as the difference between stocks at two times. It must always be remembered that it is not the magnitude of the stock that matters per se, but the change in the magnitude of the stock. When terrestrial stored carbon is sold, it is not the stock that is sold, but the flux it represents.

Carbon is held in terrestrial ecosystems in several interconnected pools of different sizes and turnover times (**Figure 1**). Turnover of some pools, such as the simple organic compounds and microbial biomass that make up the 'fast' pool, are fleeting – they may last only minutes to hours. Others, like live or dead leaves, decay over a period of months to years. Yet others, such as the trunks and coarse roots of trees, and the clay-associated organic carbon in the soil, last for decades. Finally, there are several pools that may persist for centuries or millennia such as charcoal, or the structurally complex, high

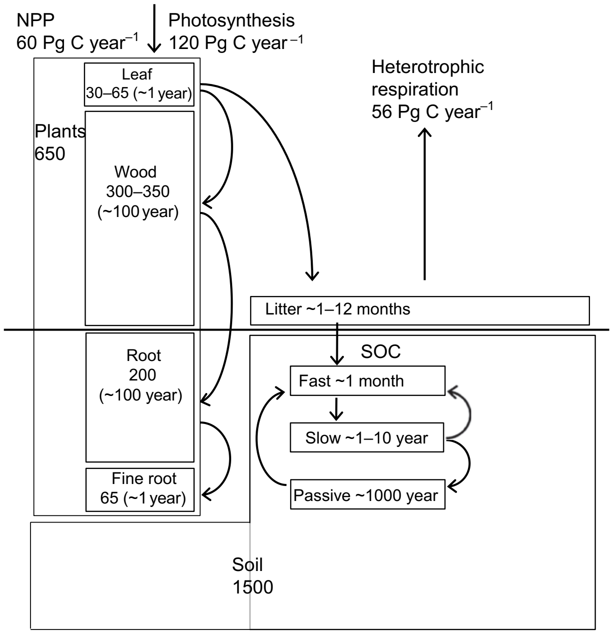


Figure 1 The key carbon stocks (boxes, Pg C) and fluxes (arrows, Pg C year^{-1}) in terrestrial ecosystems with their approximate magnitude at a global scale and the typical turnover times. The soil carbon excludes wetland soil and permafrost stocks.

molecular weight forms of soil organic carbon 'humic compounds'. The faster turnover pools are usually not counted when the carbon credits are calculated. There is an unwritten guideline that a pool must persist for 20 or more years before it is considered 'sequestered' rather than 'stored'. This aims to address the issue of the 'permanence' of land-stored carbon.

The total flux of carbon into and out of terrestrial ecosystems is always bigger than the portion of the flux that becomes stored, in most cases, one to two orders of magnitude bigger. For instance, at the global scale, over 100 Pg C year^{-1} is assimilated by the terrestrial vegetated surface through photosynthesis (Solomon et al. 2007). This overall amount is the gross primary production of the terrestrial biosphere. About half of this is directly returned through respiration by the plants themselves, leaving a net primary production of about 60 Pg C year^{-1}. In a steady state, which we would expect to be approximated in long-term undisturbed vegetation, virtually all of this would be lost back to the atmosphere through heterotrophic respiration (e.g., by microbes and animals feeding on the plants or their residues). Alternately, the carbon could be returned to the atmosphere relatively abruptly through a fire (for instance see Tilman et al. 2000) or major disturbance. In production landscapes, a significant amount of carbon is extracted through the harvest of crops or timber. A small amount of carbon is transported laterally out of the ecosystem in the form of aerosols, sediments, or dissolved organic carbon. Since the terrestrial biosphere is currently not in a steady state, about 2% of the assimilated flux is retained in terrestrial ecosystems, where it manifests as an increase in biomass, litter, and soil carbon (Malhi 2002; Solomon et al. 2007).

The small size of the stored flux relative to the turnover flux makes the accurate measurement of the former very challenging – the uncertainty in flux measurement is often larger than the stored flux. Similarly, the change in ecosystem stock is usually small, relative to the total stock, unless it is allowed to accumulate for several years. The relative error of estimation for the different components making up the global carbon stocks and fluxes range from about 1 to 90% (Scholes et al. 2009), with an average of 10–20%.

4.09.1.3 The Market for Climate Services

Despite the down turn and economic volatility in capital markets since the 2008–09 financial crisis, and a decline in carbon prices in 2011, the global carbon market amounted to USD 176 × 10^9 (Kossoy et al. 2012) in trades in 2011, making it one of the largest global commodity markets. Only a small part of this is 'land-based carbon'; the majority consists of reductions in industrial carbon dioxide or other greenhouse gas emissions. The main distinction is between the 'official market', e.g., that associated with international treaties such as the Kyoto Protocol, and the 'voluntary market'. The official market is always certified, in other words, backed up by accounting standards and audits. The voluntary markets are usually also certified, but with varying degrees of rigor. Since the signatories to international treaties are sovereign countries rather than individuals or corporations, countries are ultimately in control of the official market, and define its size through the regulations they set. The price of carbon in the official market is much higher than the price in the voluntary market, but so is the cost of participating in it.

Both the sellers and buyers of certified carbon credits are typically in the private sector. In the case of land-stored carbon, the sellers are land owners or land stewards, who through their management practices have caused the carbon density of the land (e.g., the mass of carbon within eligible classes per unit land area) to increase. In principle, the simultaneous effects of changes in the other greenhouse gases or land surface properties that also result from the management action must be considered as well, but in practice seldom are. The ultimate buyers are entities that have emission reduction commitments, which they either cannot meet or cannot do so at a price less than the market price for certified carbon credits. Between the sellers and buyers are a range of brokers and certifiers, and the agencies appointed by governments to oversee carbon trades. The complex structures and onerous certification rules add greatly to the transaction costs. Since the transaction costs do not scale proportionately with the amount of carbon involved, effectively, only large entities can trade profitably in carbon (Wise et al. 2009).

In the official market, two conditions need to be met. First, the carbon stored must be 'additional', in other words, as a result of some deliberate action, which otherwise would not have occurred. This is important, given that the terrestrial biosphere is taking up 2 Pg C year^{-1} without any intentional human assistance. In practice, since the mechanisms of the terrestrial carbon sink are not well understood, it is very hard (perhaps impossible) to attribute changes in land carbon between those arising from management and those that would have occurred anyway. Generally, a more or less arbitrary 'baseline' is agreed, and deviations from this baseline become the tradable commodity.

The second consideration is 'leakage' (Murray et al. 2004), which means that carbon storage in one location should not simply result in a carbon loss elsewhere. For instance, if a forest is permitted to accumulate carbon by restricting harvests, from where is the unchanged demand for wood being met? Again, this consideration is hard to implement with complete confidence. The usual approach is to insist on 'wall-to-wall' accounting within units large enough to encompass likely leakage, such as entire countries. If leakage is detected, it is hard to attribute it to any specific project.

The participation of 'non-Annex 1' countries (e.g., countries without emission reduction commitments, which translates mainly to developing countries) in the Kyoto Protocol carbon market is via the Clean Development Mechanism (CDM). It only recognizes a limited set of land-based storage activities (essentially, afforestation). The number of land-based carbon projects in the CDM has been low. Over and above the additionality and leakage conditions, CDM trades must demonstrate that they are consistent with sustainable development. For instance, a land carbon storage project, which results for instance in a large loss of biodiversity, water yield, or livelihoods, would in principle be disqualified.

Reduced Emissions from Deforestation and Degradation (REDD) introduces a new concept to the carbon trade. Instead of paying for the (imperfect) restoration of carbon on deforested land, it aims to pay a maintenance fee to keep the carbon on the land in the first place, while incidentally protecting biodiversity, water yield, etc. (Strassburg et al. 2009; McAlpine et al. 2010). This is a particular case of a general concept known as Payment for Environmental Services (PES). The principle difficulties with REDD involve monitoring what is cost effective, but nevertheless has sufficient sensitivity to detect partial loses (degradation); avoidance of leakage; ensuring that the land custodians are the major beneficiaries of the payment; and determining a reasonable price, given that the payments occur year after year, potentially forever – more like rental of stored carbon than a purchase of a change in stock.

4.09.2 What Controls the Magnitude of the Service?

In general, the carbon storage-related climate service offered by ecosystems is finite, since it represents an adjustment to a new equilibrium between carbon uptake and carbon loss. Once the equilibrium is reached, the net flux is zero and the stock quantity is unchanging in the long-term, even though large turnover might be taking place. Exceptions to this 'limited time' feature occur in the cases where carbon is continuously exported in a sequestered form (such as timber), or the captured carbon is used as a substitute for fossil fuels (e.g., biofuels), or in the 'rental' agreement in REDD. The service in general can be thought of as having a rate and a duration whose product constitutes the magnitude. Net primary productivity (NPP), ambient temperature, and soil waterlogging are the key determinants of the rate. The upper limits of soil carbon storage and biomass set the total magnitude.

4.09.2.1 Productive Potential

Terrestrial ecosystems cannot accumulate carbon at a rate exceeding net primary production. In practice, they generally store carbon at a much lower rate; nevertheless NPP is a good first order indicator of locations with high storage potential versus low storage potential. The broad-scale predictors of terrestrial NPP are well known: The absence of water stress, warm but not excessively hot temperatures, sufficient solar radiation, and a sufficient supply of the essential elements needed for plant growth (Running et al. 2004). The constraints applied by the carbon market – high transaction costs and the necessity for relatively frequent periodic inventories, means that ecosystems with low NPP, even if they technically could store a lot of carbon thanks to their large area – are not financially viable as storage locations. The carbon increment per area over a 5-year period is too low to detect except with an inordinate investment of effort.

Different broad ecophysiological groups of plants – plant functional types or PFTs (Grime 1977; Box 1996) – have different characteristic carbon uptake rates and sensitivities to environmental drivers. Some of the key top-level PFTs are plants with 'conventional photosynthesis', the C_3 pathway (most trees, herbs, temperate and wetland grasses, crops such as wheat and rice); C_4 photosynthetic systems (tropical grasses and crops derived from them, such as sugarcane and maize); and Crassulacean Acid Metabolism (CAM) succulents. The distribution of PFTs shows geographical patterns related to the climate, and specifically to water stress, and temperature.

Plants with CAM (including Agave, Cactus, and *Portulacaria afra*) are able to maintain productivity under conditions of severe water stress by temporally decoupling the carbon assimilation processes from the transpiration process. This may allow them to accumulate carbon at unusually high rates even in arid areas, but it does not relieve them totally from water constraints (Osmond 1978). The measured water use efficiency is about twice that of C_3 plants, but only a little better than that achieved by C_4 plants (Winter et al. 2005).

4.09.2.2 Mean Temperature

Other factors being equal, cool locations accumulate more soil organic matter and biomass than hot locations (Jenny 1980). This is apparent on altitudinal gradients – Montane forests have a higher carbon density than lowland forests, for instance, and on latitudinal gradients within, for instance, the Great Plains of North America (Parton et al. 1987). The reason is the strong and exponentially increasing effect that high temperatures have on increasing respiration rates, whereas carbon assimilation rates initially increase with temperature, but peak and decline above around 30 °C.

4.09.2.3 Waterlogging of the Soil

Soils which are waterlogged for more than a few weeks become anaerobic. Decomposition continues, but at a much reduced rate and via a methanogenic pathway rather than one that produces CO_2. These soils accumulate large amounts of carbon in the form of peat, both in temperate-cool areas and in nutrient-poor regions of the tropics (Hooijer et al. 2010). Paradoxically, flooding a soil for this purpose is counterproductive, because the methane and nitrous oxide generated offset the carbon gain (Sampson and Scholes 2000). Conversely, draining a peat box releases carbon dioxide, but eliminates a source of methane, and the two effects more or less cancel each other out.

4.09.2.4 What Determines How Much Carbon a Soil Can Store?

The global amount of carbon stored in soils vastly exceeds that stored in plant biomass or the atmosphere (1500–2000 Pg C for soils, 466–654 Pg C for biomass, 750 Pg C in the atmosphere; Prentice et al. 2001). Aside from the special case of waterlogged soils, described above, the maximum amount of carbon a given soil can store is mainly controlled by its texture (the fraction of clay and silt it contains) (Jenny 1980; Parton et al. 1993; Schimel et al. 1994) and the mineralogy of the clays (Six et al. 2002; Denef et al. 2004). The key slow turnover carbon pool in the soil is intimately associated with clays, and especially with large surface area clays such as smectites and illites (Six et al. 2002) (**Figure 2(a)**). Clayey soils facilitate the formation of C pools with slow turnover times due to the physical protection of SOM by clay minerals (Christensen 1992; Silver et al. 2000).

Once this storage surface is occupied, carbon can further accumulate as particulate organic carbon (tiny fragments of biomass), but is susceptible to relatively rapid loss (Six et al. 2002). Shallow or very stony soils can also not accumulate large amounts of carbon. Soil organic carbon stocks vary across ecosystems (**Figure 2(b)**) due to complex interactions among biotic and abiotic factors (Six et al. 2002; Schmidt et al. 2011).

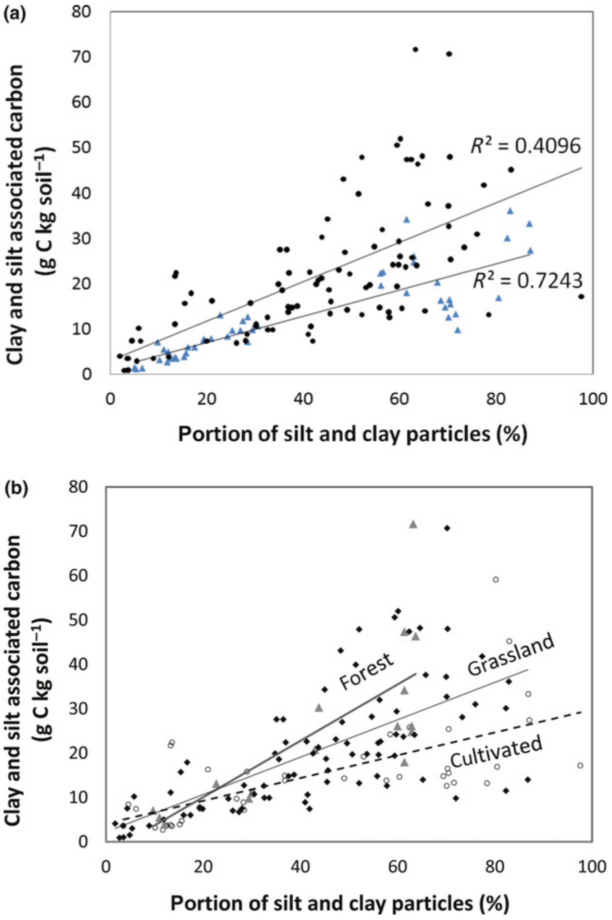


Figure 2 Silt plus clay content ('fines', as %) and silt and clay associated carbon concentration (g C kg soil^{-1}) for mineral particles 0–20 μm. (a) The effect of clay mineralogy (1:1 clays, e.g., kaolinite and serpentine, blue triangles; 2:1 clays, e.g., smectite and illite, black circles). (b) In relation to the type of ecosystem. Redrawn from data appendices in Six, J., R. T. Conant, E. A. Paul, and K. Paustian, 2002: Stabilization mechanisms of soil organic matter: implications for C-saturation of soils. *Plant Soil*, **241,** 155–176.

4.09.2.5 What Determines the Maximum Biomass on a Site?

The aboveground biomass that can accumulate on a site is determined by the vegetation cover and its height. Cover increases with rainfall, up to a maximum of essentially continuous canopy (Sankaran et al. 2005). Further biomass increases beyond this point rely on increasing height. The fundamental limits to the height that trees can reach are set by biomechanical considerations, such as the ability to anchor the tree against winds and the ability to lift water to the leaves (Koch et al. 2004). The importance of height, and the woody structural tissues needed to attain it, is why forests are the carbon storage ecosystems of choice. Ecosystems can store a substantial amount of carbon belowground, in the form of fine and coarse roots (Jackson et al. 1997), but belowground carbon does not count in many carbon market schemes, for no logical reason except that it is hard to see and tedious to measure.

4.09.2.6 Effects of the Disturbance Regime

Many terrestrial carbon storage projects involve the exclusion or reduction in frequency or intensity of disturbances that would otherwise lead to carbon loss. For instance, fire exclusion in savannas and grasslands, reduced-impact logging in forests, or reduced tillage in crop agriculture. The main disturbances, which disrupt the carbon cycle and can cause the loss of accumulated carbon, are fires, insect herbivore outbreaks, windstorms, harvest of plant material by humans, and disruption of the soil by cultivation or drainage. These disturbances are neither mutually exclusive, nor independent of one another. For instance, the dead material caused by a pest outbreak can increase the risk of fire.

Disturbance is often characterized as if it were a simple binary variable. Does it occur or not? In reality, disturbance regimes consist not only of the probability (or, equivalently, the frequency) of occurrence, but also the intensity of the disturbance and often more subtle characteristics, such as their relation to phenological or growth stages and their coincidence with other disturbances. A change to any of the determinants of a disturbance regime is likely to have consequences for the carbon cycle (e.g., in tropical savannas; Bird et al. 2000; Aranibar et al. 2003), but not all effects will be dramatic. Small changes in the regime will generally result in small changes to the stored carbon.

It is possible for an ecosystem to accumulate carbon in the presence of disturbances, provided that the carbon lost as a result of the disturbance is less than the carbon accumulated between disturbances. For instance, it is possible for a 'production forest', in which trees are felled rotationally to nevertheless have a higher average carbon density than a non-forested site (although probably less than an unharvested forest, **Figure 3**). Exactly how much more depends on the specifics of the management regime – how often does harvest

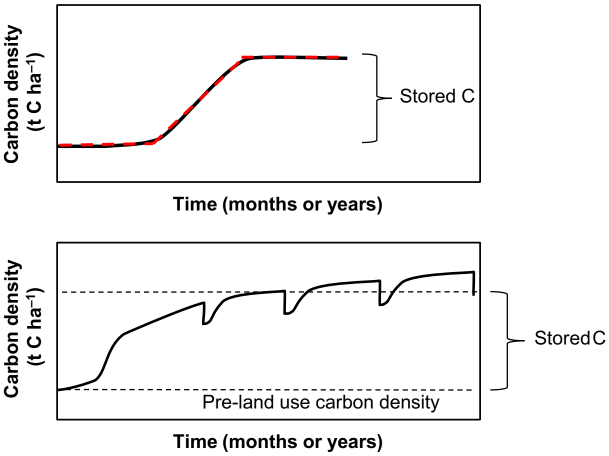

Carbon density (t C ha^{-1})
Stored C
Time (months or years)
Carbon density (t C ha^{-1})
Stored C
Pre-land use carbon density
Time (months or years)

Figure 3 A schematic representation of an ecosystem accumulating carbon following a change in land management. The top panel shows a simple case, where the carbon density rises according to a more or less logistic curve to a new equilibrium level. This can be approximated with linear segments defining a rate and duration of carbon storage. The lower panel shows a case, such as a rotationally harvested plantation, where there are repeated logistic segments interrupted by harvest or disturbance events. The long-term mean carbon density is nevertheless higher than in the preland use change case.

occur, what fraction of carbon is removed, and how much collateral damage is caused.

It is important to tolerate some level of disturbance in terrestrial ecosystems under management for carbon storage for several reasons. Firstly, an evolutionarily appropriate disturbance regime is required to maintain ecosystem characteristics such as biodiversity. Secondly, small disturbances help to preempt large disturbances (this point is discussed in more detail in Section 4.09.5). Thirdly, there is a theoretical argument (largely untested empirically) that protection from disturbances leads to the gradual loss of system capacity to cope with disturbance when it inevitably occurs – in other words, a loss of resilience (Gunderson and Holling 2002).

4.09.3 Thresholds and Tipping Points

4.09.3.1 Feedbacks in the Terrestrial Carbon Cycle

Feedback occurs when a change in one element of a system generates a response, propagated through the rest of the system, that eventually returns to have an effect on the first element that changed. Feedback is 'negative' (or stabilizing) when its net effect is to dampen the initial change and 'positive' when the net effect is to amplify it. Where more than one feedback pathway exists and the signs are different, the net effect can still be calculated, but this requires knowledge of the relative magnitudes of the individual effect terms and their nonlinear interactions. Positive feedbacks can lead to 'runaway change' if they are sufficiently large, but do not necessarily do so. In general, the effect of a positive feedback is simply to increase the size of the initial perturbation somewhat. If the net feedback effect is larger than the initial perturbation, the system is said have crossed a threshold, a 'tipping point' in popular terms, and will move under its own internal dynamics into a new stability domain. As a result of such interactions, new states can develop (Peters et al. 2004). There is an obvious positive feedback loop of terrestrial carbon with the rest of the climate system. An increase of temperature leads to the release of carbon from soils, which could lead to a further increase in temperature from the added radiative heating. But within plausible ranges of near future warming, the feedback by this mechanism alone is not believed to be strong enough to cause 'runaway warming' (Prentice et al. 2001). In conjunction with speculated (but not demonstrated) effects such as a large increase in vegetation fires, or a large accompanying release of methane from frozen soils, a runaway scenario leading to a persistently much warmer future state of the Earth's climate system may be possible.

4.09.3.2 Tipping Points

Moderately complex systems exposed to external forcing do not change smoothly and gradually, especially where some or all of the effect links between elements are themselves nonlinear, or lagged in time (e.g., Scheffer and Carpenter 2003, Rial et al. 2004). Rather, they appear to resist change or be insensitive to applied driving forces over some domain, and then change more or less abruptly. The climate system, including its biospheric and human system couplings, has all these characteristics. Therefore, the response of the terrestrial carbon cycle to increased effects from atmospheric and other climatic effects is unlikely to be continuous and incremental at the global spatial scale.

The terms 'tipping point' and 'threshold' have been used in a variety of ways in this context, not always consistently (Raupach and Canadell 2008; Lenton et al. 2008). The notions also become confounded with other limit-based ideas, such as (1) the amount of change that is policy relevant, (2) ethically important, (3) important for human welfare, and (4) ecologically important (Lenton et al. 2008; Kriegler et al. 2009; Martin et al. 2009). Often 'threshold' is used to describe either a more or less arbitrary level, which people agree not to transgress. Alternately, it may describe a point where the rate of change begins to steepen, but does not yet constitute a separation between two system states. The terrestrial carbon system has many such thresholds, which are important, but not necessarily critical.

In this chapter we use 'tipping point' exclusively to refer to a threshold where the internal dynamics of the system cause it to continue to change after the forcing effect has ceased, carrying the system quasi-irreversibly into a new state. Beyond the tipping point, the future state and development of the system is qualitatively different (Lenton et al. 2008). We consider it only 'quasi-irreversible', because although in the short term the system will not revert of its own accord, it may be possible to manage it back to the former state with some input of effort. In the longer term, another series of changes may be triggered, which eventually lead the system back to its original state.

Inherent in the notion of tipping points is the idea that a small perturbation in their vicinity can have potentially disproportionate, persistent impacts on the system. Such tipping points have been suggested to exist for several subsystems or spatial regions of the global terrestrial carbon system, within the plausible range of contemporary environmental change.

For instance, the melting point of ice near 0 °C constitutes a physically determined threshold with important consequences for the carbon cycle of frozen soils. If large areas of permafrost melt, their contribution to global atmospheric CO_2 and methane, plus the darkening of the surface resulting from pools of water, makes it increasingly unlikely that they will spontaneously refreeze – to do so would require a sustained return to a much cooler climate. Another example, which has been suggested, is the susceptibility of tropical rainforests to fire if they experience prolonged dry spells. Once the forest burns, the canopy is opened up, favoring the growth of grasses, which in turn makes future fires more likely. These examples are elaborated below.

4.09.3.3 The Hypothesis of Terrestrial C Sink Saturation

The likely presence of thresholds can sometimes be predicted from a qualitative knowledge of the form of the interactions in a system. For instance, both heterotrophic and autotrophic respirations increase with rising temperature. The relationship is conventionally represented by an exponential function. Furthermore, the respiration rate is more or less proportional to the soil carbon and biomass pools, respectively. The global mean temperature, over multi-year timescales, is approximately proportional to the global atmospheric CO_2 concentration. On the carbon uptake side, photosynthesis on land is a saturating function of atmospheric CO_2 and a hump-shaped function of temperature with a peak below 30 °C. Scholes (1999) and Kirschbaum (2000) both speculated that the consequence of this set of interactions would be that the land would initially be an increasing carbon sink, as photosynthesis rose in response to rising atmospheric CO_2 concentration. The sink would peak and then decline (eventually becoming a net source) as respiration, in response to rising temperature and accumulating C stocks, caught up with and overtook photosynthesis.

There is a second reason to expect the terrestrial biosphere to behave initially as a sink, but later to become a source, before returning to approximate neutrality. The time lags intrinsic to the terrestrial carbon cycle – the life span of a tree, for instance, or the turnover rate of soil carbon – means that there is inevitably a delay between photosynthesis and respiration, since the carbon must first be captured before it can be respired.

Subsequent detailed quantitative and spatially explicit modeling efforts have tended to substantiate these qualitative predictions (Canadell et al. 2007). Most global climate models with a global C cycle model suggest that the current net global terrestrial carbon sink could peak in the twenty-first century and then decline, in some cases smoothly to a new equilibrium between respiration and uptake, but more often with some overshoot in favor of respiration (Friedlingstein et al. 2006). Carbon in the 'fast turnover' soil pool has a higher temperature dependency than more 'passive' soil carbon, and it is the increased turnover of this labile soil carbon, which contributes to the sink saturation rather than the release of recalcitrant carbon from the 'slow' pools (Fang et al. 2005; Knorr et al. 2005).

4.09.3.4 A Plausible Amazon Drought Tipping Point

One of the possible 'inevitable surprises' (Lenton et al. 2008) on the IPCC short list of plausible abrupt climate change scenarios (Solomon et al. 2007) is modification to the extent, structure, and behavior of the rainforest in the Amazon Basin. A combination of changes in tree fraction, regional rainfall, and summer temperatures, due to a complex interplay between land use change, and anthropogenic and natural climate forcing is simulated, which in some models induces a partial dieback in the Amazonian rainforests (Cox et al. 2000, 2004; Betts et al. 2004; Malhi et al. 2009).

The majority of precipitation in the Amazon basin is recycled, e.g., it originates from water vapor evaporated in the basin itself. Therefore a change in the land surface – deforestation, or shift to more savanna-like species – could in principle lead to a positive feedback in the water cycle of the region (**Figure 4**). Modeling results hypothesize that dry-season water stress could increase in the twenty-first century, promoting a climate, which supports a seasonally deciduous forest (Malhi et al. 2009) or an open woodland with grasses (Betts et al. 2004; Cox et al. 2004), rather than the present evergreen forest. Such a state change could further reduce regional rainfall due to a reduction in hydraulic redistribution (Lee et al. 2005) and increase the regional temperature. It would also release CO_2 to the atmosphere. Higher atmospheric CO_2 also leads to stomatal closure, further reducing evaporation and ultimately, precipitation Costa and Foley (2000). Higher temperatures and reduced rainfall lead to reductions in NPP (Betts et al. 2004; Cox et al. 2004), and make the biomass carbon in the replacement seasonal forests vulnerable to fires (Malhi et al. 2009). Rainforest trees seldom experience fire and are therefore susceptible to fires in the litter layer and the near-ground vegetation. Generally the ground vegetation is kept sparse by the closed tree canopy and the litter layer is too wet to burn. A dry spell lasting several months can dry out the litter layer. If land clearing activities damage the forest margin, allowing fire in, the canopy trees can be killed, which lets in light, allows grasses to spread, and makes future fires more likely. A further feedback on rainfall could occur through the increased number of aerosols and cloud condensation nuclei produced by burning (Andreae et al. 2004).

4.09.3.5 Permafrost Melting

Estimates of the size of the carbon stocks in permanently frozen (permafrost) soils vary from 200–800 Pg C (excluding wetlands; Gruber et al. 2004), 400 Pg C (northern hemisphere only, Tarnocai et al. 2009), 900 Pg C (Zimov et al. 2006) to 1672 Pg C (in the northern circumpolar permafrost zone, including 277 Pg in peatlands (Schuur et al. 2008).

Schuur et al. (2008) show that permafrost thawing is not just driven by increased air temperature causing CO_2 release due to temperature sensitive decomposition. It includes other energy balance and physical processes (**Figure 5**). In thawing areas where ground-ice content is high, the risk of regional carbon loss through soil subsidence (thermokarst) and erosion increases (Schuur et al. 2008). While the heterogeneity and adaptiveness of soils makes the parameterization of turnover times a nontrivial task (Knorr et al. 2005; Davidson and Jassens 2006) we know that an increase in the rates of thawing and warmer soil temperatures would result in greater heterotrophic respiration. Assuming a temperature increase of 2 °C, up to 5 Pg C could be released from melting permafrost over a period

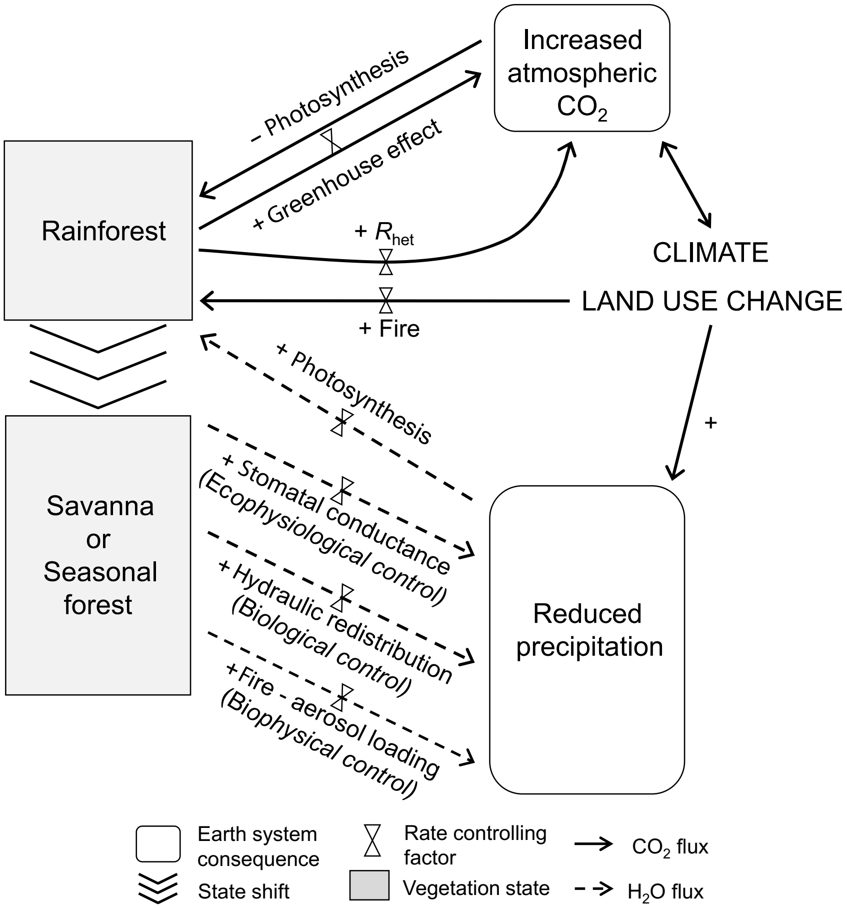

Increased atmospheric CO_2
– Photosynthesis
+ Greenhouse effect
Rainforest
+ R_{het}
CLIMATE
LAND USE CHANGE
+ Fire
+ Photosynthesis
+
Savanna or Seasonal forest
+ Stomatal conductance (Ecophysiological control)
+ Hydraulic redistribution (Biological control)
+ Fire - aerosol loading (Biophysical control)
Reduced precipitation
Earth system consequence
State shift
Rate controlling factor
Vegetation state
CO_2 flux
H_2O flux

Figure 4 Some of the key interaction that has been postulated to lead to a 'tipping point' in the Amazon basin. The CAPITALS indicate driving factors, the boxes are system properties, the arrows indicate effects (with the sign noted), and the bow-ties (⧖) indicate the controls over these effects.

of 20 years, and up to 100 Pg C over 100 years (Gruber et al. 2004). Therefore, the vulnerability of permafrost carbon stock to temperature increases is potentially the most important feedback of terrestrial carbon within the climate system.

4.09.4 Vulnerability of the Terrestrial Climate Regulation Service to Climate

Here we follow the conventional vulnerability assessment approach, which considers vulnerability to be the product of exposure to a threat, sensitivity to that threat, and (lack of) capacity to adapt to the threat. We will consider adaptive capacity within a resilience framework that does not restrict the adaptations to those which keep the system more or less as it was, but allow it to transform to new states.

One 'threat' is surface temperature increases in conjunction with either increasing or decreasing water stress, depending on the region. Equally important are the accompanying changes in the probability of extremes of heat and cold, flooding or drought, and the changes in disturbance regimes which they can trigger (Field et al. 2012). Indirect effects include changes in the exposure to pests, diseases, and fire. Surface temperature change is just one of a series of environmental effects, such as rising CO_2, nitrogen and sulfur deposition, land management practices, and declining biodiversity. Exposure to this syndrome of stresses is spatially variable, but no part of the terrestrial biosphere is immune from them.

In evaluating 'sensitivity' we have drawn on two ideas developed above, the form (shape) of the relationship, and the sign and strength of any feedbacks that exist. Sensitivity is low if a change in the 'threat' parameter produced a much less than proportionate change in the outcome of an affected system, and high if the effect is more than proportionate. A concave functional response (one that becomes progressively steeper as the size of the driving threat increases) is initially insensitive, but becomes highly sensitive beyond some point. Convex or saturating functions, on the other hand, become progressively less sensitive. A threshold response is one with an abrupt point at which they become sensitive. Sensitivity needs to be explored over timescales of decades to centuries, given that many of the processes are gradual and the pools can be long-lived (Table 1).

Several approaches have been applied to evaluating the sensitivity of carbon fluxes and pools to climate. Gruber et al. (2004) used a risk-assessment approach incorporating expert opinion. The C^4MIP experiment (Friedlingstein et al. 2006) used complex climate models with a carbon cycle. Raupach and Canadell (2008) used a less numerically intensive 'perturbation-based approach' in which they compare the effects of a disturbance in coupled and uncoupled semiquantitative models.

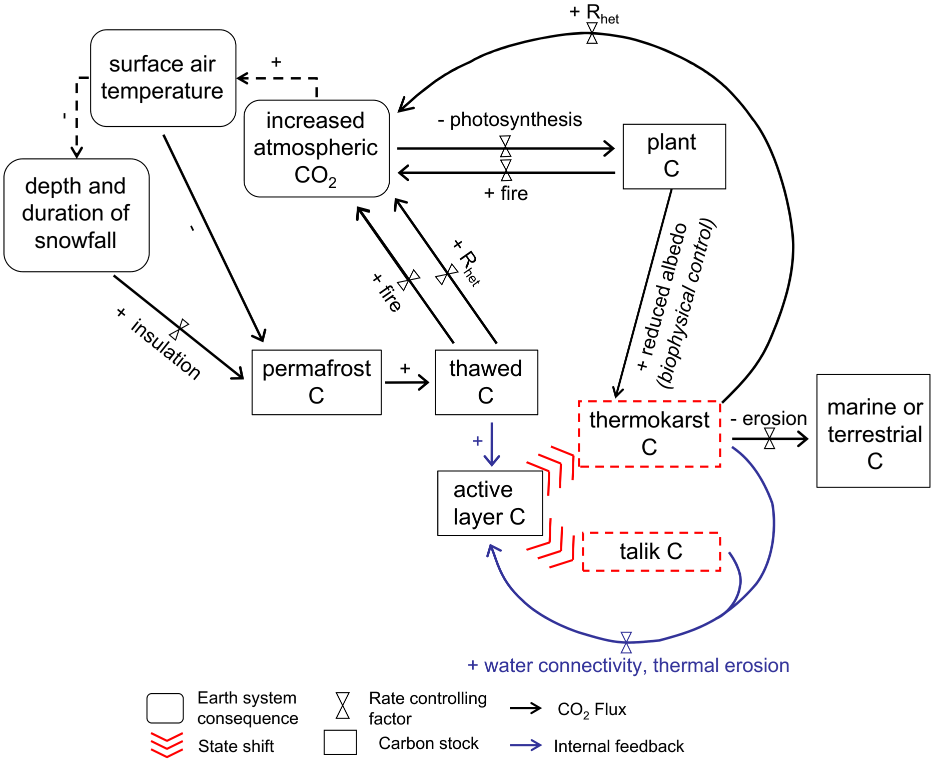

+ R_{het}
surface air temperature
+
depth and duration of snowfall
increased atmospheric CO_2
- photosynthesis
+ fire
plant C
+ R_{het}
+ fire
+ insulation
permafrost C
+
thawed C
+ reduced albedo (biophysical control)
thermokarst C
- erosion
marine or terrestrial C
+
active layer C
talik C
+ water connectivity, thermal erosion
Earth system consequence
Rate controlling factor
CO_2 Flux
State shift
Carbon stock
Internal feedback

Figure 5 Permafrost melting includes direct and indirect feedbacks involving physical changes to the soil column, changes in surface brightness and fire. Summarized from Schuur, E. A. G., and Coauthors, 2008: Vulnerability of permafrost carbon to climate change: implications for the global carbon cycle. *BioScience*, **8,** 701–714.

4.09.4.1 Fire

Variation in the areas burned is responsible for a significant part of the variation in the annual CO_2 balance (van der Werf et al. 2006). Over a course of season, year, or longer term depending on the ecosystem, the terrestrial carbon losses from fires are generally compensated for by gains in biomass as vegetation regrows following a burn, but if changes in land use, land management, or climate affect the frequency or intensity of fires, the recovery may be less than complete, or overcompensate. It is during such periods of regime transition that long-term trends in carbon accumulation change from net uptake to net release, or vice versa (Raupach and Canadell 2008).

Fire can occur in almost all terrestrial biomes, but the current extent of fires and the quantity of carbon consumed are concentrated in the tropical savannas and the boreal forests (van der Werf et al. 2010). The area burned in savannas annually is very large, but the fires consume relatively little fuel per unit area, since they burn mostly dry grass, leaving the trees intact.

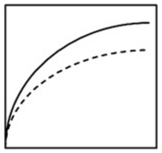
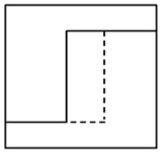
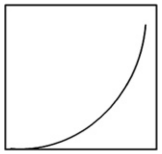
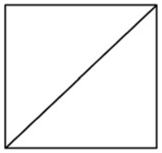
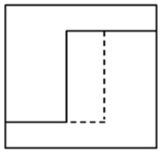
Boreal forests are one of the largest world biomes. Some estimates have them storing over one-third of terrestrial biospheric carbon, particularly in the form of forested peatlands (Kasischke et al. 1995). Approximately two-thirds of the boreal forests lie in the Russian Federation, with the rest falling mostly in Canada and Alaska (Wooster and Zhang 2004). The landscape is a matrix of different forest types, each storing differing amount of carbon. Together with differences in the severity of the fire, this affects the total direct carbon emissions from fires in boreal forests by as much as 50%. The emissions in extreme fire years are 37–41% greater, due to soil organic matter combustion (Soja et al. 2007). The probability of more fire in boreal forests in the future is high (Achard et al. 2008), with consequences for the global carbon cycle (Conard and Ivanova 1997; Soja et al. 2007).

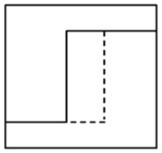
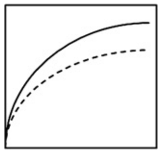
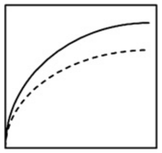
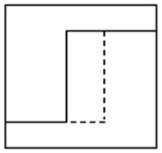
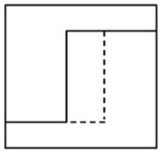
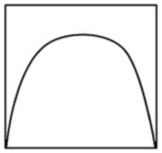
4.09.4.2 Heatwaves

Episodes of above average temperature with or without below average rainfall have the potential to significantly alter carbon fluxes and stocks. For example, Europe experienced a heat wave in the summer of 2003, with July temperatures up to 6 °C above long-term means and annual precipitation deficits up to 300 mm year^{-1}, about 50% below the average (Ciais et al. 2005). A significant reduction in gross primary productivity (GPP) was experienced throughout the continent (Ciais et al. 2005). The productivity of the temperate forest and grasslands ecosystems (Ciais et al. 2005; Granier et al. 2007) and croplands (Granier et al. 2007) Europe-wide was affected. A dramatic reduction in crop yield occurred in France, Italy, and south Germany. Tree radial growth was reduced especially in the year following the drought (Granier et al. 2007).

Both autotrophic and heterotrophic respirations were controlled by water availability to varying degrees across Europe (Grainer et al. 2007). Although 2003 is not the driest year on record, the impacts of the water stress was amplified by the high summer temperatures and soil water deficits carried

Table 1 A classification and evaluation of vulnerabilities, based on the expert opinion of the authors, informed by a review of the literature. For a definition of terms, see the text

Driver of change ('Threat')	*Affected system*	*Sensitivity and form of relationship*		*Adaptive capacity*	*Vulnerability outcome*
Changes in surface temperature	Carbon in non-wetland, non-frozen soils	High and concave		Microbial communities change, but respiration still increases with increased temperatures	High
	Carbon in permafrost soils	Very high and controlled by a threshold		None	Very high
Increasing or decreasing water stress	Wetland soils (peats)	Convex for further wetting of wet systems, threshold for drying below limit for wetland persistence		Loss (or gain) of C compensated by decrease (increase) in CH_4 emission	Medium
	Net primary production	Linear, with a threshold for extreme droughts		Results in long-term species composition shifts but NPP remains affected. Higher diversity helps	Medium
Extreme wind and rain events	Forest biomass	Threshold effect where winds exceed bending or root strength tolerance		High recovery in systems with a history of exposure, occurs through succession	Low

Fires	Biomass, especially of trees, and litter layers or peat	Threshold effect for unadapted systems, concave for adapted systems	 	Replacement by fire-adapted vegetation, but net reduction of stored C	High
Pest outbreaks	Biomass and net primary production	Concave, thresholds for some pests; interaction with fire	 	Long term re-equilibration between predators and prey. Higher diversity may help	Medium
Land use change	Soil and biomass C	High, often a threshold effect use type changes rather than use intensity		High adaptive capacity through policy (e.g., REDD) and innovation	High
N and S deposition	Tree biomass	Hump-shaped curve – initial stimulation, depression at high cumulative levels		Long-lasting ecosystem function, composition and structure changes. Technological adaptive capacity to reduce deposition	Medium

over from the previous spring (Ciais et al. 2005). Because both GPP and the respiration fluxes were reduced, the absolute decrease in NEE was smaller than the reduction in GPP (Ciais et al. 2005; Grainer et al. 2007). The consequence for the net carbon balance was that European temperate forests became a strong net source of carbon dioxide (0.5 Pg C year^{-1}), which reversed the effects of four preceding years of net ecosystem carbon sequestration (Ciais et al. 2005).

An analysis of the northern hemisphere terrestrial carbon fluxes shows that since 1994, the enhanced carbon uptake due to a progressively earlier spring has been canceled by decreased uptake during summer, due largely to hotter and drier summers in the mid and high latitudes (Angert et al. 2005). Enhanced productivity with warmer temperatures and longer growing seasons might be counterbalanced by more frequent heat and drought events. Thus, although the forests of the world currently constitute a large sink (Yude et al. 2011), the reliability of this sink under hotter, sometimes drier, more variable climates could be spatially and temporally more variable.

4.09.4.3 Increases in Rainfall, Decreases in Rainfall, and Prolonged Droughts

The interannual variability of the growth in atmospheric carbon dioxide is largely due to variability in the terrestrial term. Most of that variability is located in the tropics, a large fraction of which is in Africa. The variation is strongly associated with climate indices such as ENSO. It is inferred that much of the variation is due to the source or sink behavior of the tropical season savannas rather than the continuously moist evergreen rainforests. A multi-year record of carbon fluxes exists for the flux station at Skukuza in South Africa that supports this argument. The site is a carbon sink during wetter-than-average years, and a source during drier than average years. Overall, over the period of record, it has been a source (Archibald et al. 2009a).

A disproportionate part of the interannual variation in Fraction Absorbed Photosynthetic Radiation (FAPAR) in this mixed tree-grass system is due to the grasses. As has been observed in other savannas, the tree leaf area duration varies little from season to season, but the grass leaf area is highly dependent on rainfall (Archibald and Scholes 2007). Contrary to conventional wisdom, the area burned in African savannas and the amount of biomass consumed by fire both decrease in dry years, because the available fuel decreases (Archibald et al. 2009b).

4.09.4.4 Windstorms

Windthrow of trees is one of the most common disturbance dynamics in forests. An example involving a tropical hurricane in Puerto Rico is described by Walker (1991) and its carbon cycle consequences are explored by Sandford et al. (1991). They found a net release of carbon dioxide resulting from the loss of foliage and the increase in the litter and dead wood pools, but a relatively rapid return to net sink status as the rapidly growing trees establish a complete cover. Long-term simulations suggest that the forest can continue to be a net sink of carbon, on average, even with a major hurricane disturbance once a century.

Knohl et al. (2002) measured carbon exchange from an area of Siberian temperate forest 2 years after a major storm disturbance. They found a daytime sink, but a larger respiration source once the nighttime fluxes were added. From the quantity of downed timber and the observed log decay rate, they concluded that the storm event would have consequences for the carbon balance of the site for decades. Kramer et al. (2004) followed the carbon dynamics across wind-disturbed stands of various ages in Alaska and found remobilization and transport of carbon between fractions in the soil and vegetation.

These examples suggest that carbon stores are relatively robust to windthrow disturbances, but if the frequency of severe windstorms were to increase, the mean landscape stored carbon would be somewhat reduced.

4.09.4.5 Insect Attacks

The impact of insects on forest carbon dynamics is not only felt through the reduction in carbon uptake due to canopy loss, but also through increases in future carbon dioxide emissions from the decay of the killed trees (Kurz et al. 2008). In western Canada, the unprecedented severity and extent of the Mountain pine beetle (*Dendroctonus ponderosae*) outbreak experienced over the last decades has been attributed to two major factors: (1) a larger extent of suitable pine hosts due to forest stand maturation and (2) an expanded distribution range of the Mountain pine beetle due to warmer and drier weather (Kurz et al. 2008).

4.09.5 Ways of Reducing Vulnerability

Vulnerability can in principle be reduced by addressing any of its three components: reducing the level of the threat; reducing the sensitivity of the system; or increasing the adaptive capacity. Reducing the threat, for instance, requires policy approaches to minimize the impact of human climate forcing on the climate system (e.g., Metz et al. 2007; Pielke 2010), since the scope for reduced sensitivity and increased resilience has limits: mitigation efforts must be sufficient to keep the terrestrial biosphere within an adaptable domain. The following broad classes of actions have been proposed as ways of reducing sensitivity or increasing resilience.

4.09.5.1 Preemptive Microdisturbances

A hypothesis of resilience theory (Gunderson and Holling 2002), paraphrased in the context of carbon storage, is that systems cycle through phases of accumulating biomass and connectivity, leading to increased vulnerability, collapse, reconfiguration, and rebuilding. The implication is that these are inevitable phases, but the rate of progression through them could be manipulated by management. One approach is to deliberately initiate small destruction–reorganization cycles during the accumulating phase, in order to extend it and preempt a catastrophically large reorganization. In some ways this is similar to the ‘intermediate disturbance hypothesis’ (Connel 1978), which suggests that biodiversity and ecosystem function are maximized neither under a zero disturbance, nor under a maximal disturbance regime, but under some intermediate regime. A practical example is the use of small, frequent fires in forest or woodland management to prevent the build up of fuel that would eventually lead to a large fire that consumed more biomass in total, or damaged the capacity of the system to recover (Richards et al. 1999; Beverley et al. 2009).

4.09.5.2 Maintaining Ecosystem Function and Biodiversity

Preserving the integrity of ecosystem processes has been suggested as a necessary condition for maintaining both the buffering capacity of ecosystems (e.g., reducing sensitivity) and adaptive capacity (e.g., Smithers and Smit 1997). It is often inferred that maintaining biodiversity (in its broad sense – not only what species are present, but their relative abundances and within species genetic variability, as well as the landscape-scale structural, compositional, and functional diversity of ecosystems) is a proxy ecosystem integrity. The exact links between the various aspects of biodiversity and the dimensions of ecosystem function remain unclear, but there is empirical evidence that they exist (Zavatela et al. 2010). They may account for only a portion of adaptive capacity and buffering, may relate more to the diversity of functional groups rather than species per se, and are likely to be saturating functions, which level off at levels of biodiversity substantially below the maximum (Díaz et al. 2005).

4.09.5.3 Reducing Vulnerability to Social Change

It is increasingly indefensible to regard ecosystem change as divorced from social change. In reality they are intimately linked as social–ecological systems (Folke 2006; Chapin, this volume). Very frequently the change dynamics are initiated within the human part of the system, or the feedback processes operate via the human system. Land use change, leading to land cover change, is a major vulnerability of soil and biomass carbon (Marland et al. 2003). It is principally controlled by demographic, political, and economic factors (Lambin et al. 2001), but there may in the century timescale be climate feedbacks, as areas formerly suitable for certain uses become unsuitable, and new areas become suitable. The key vulnerability reduction actions are related to policy: what land uses may be practiced, who has rights to practice them and with what security of tenure; who pays for externalities such as those due to human climate forcing; and what prices (including subsidies) are paid for the various land-based commodities. The general recommendations for increasing the resilience of social-economic systems involve creating a sense of local ownership, stewardship and reward, effective multiscale participatory governance, and enhancing adaptive capacity through leaning and innovation (Berkes et al. 2003).

4.09.5.4 Dealing with Vulnerability in the Climate Service Market

The discussion which follows is not about reducing the fundamental vulnerability of land-based climate regulation services, but on how to establish a viable market-based service for carbon in the presence of that vulnerability. In particular, it addresses the problem of the impermanence of stored carbon on land.

There are two main approaches. The first is based on portfolio theory. By increasing the scale of projects, including different types of projects that are assumed to have uncorrelated risks, and taking to market a service that is smaller than the total amount within the portfolio, it is possible to reduce the variability of carbon services product below the fundamental variability of the service at any given location (Laurikka and Springer 2003).

The second approach is to treat the climate service as a renewable short duration contract, rather than a permanent asset. In other words, the client rents the service on a year-by-year basis for as long as it persists, rather than purchasing it outright. This is consistent with the observation that the terrestrial carbon storage service is a flux (a change in stock) rather than a stock itself. This is the logic behind the field of PES, of which REDD is a specific example relating to the climate service and also to biodiversity and other ecosystem services (Kindermann et al. 2008).

4.09.6 Trade-Offs between Climate Regulations and Other Ecosystem Services

When single-mindedly maximized, provisioning services (such as carbon sequestration) occur at the detriment of competing provisioning services, most regulating services, and sometimes cultural services (Millennium Ecosystem Assessment 2005). For instance, if a monocultural tree plantation were established in a formerly biodiverse and water limited area, the river flow would decrease, and biodiversity would be lost, as would the opportunity to grow other crops or to graze the land. If maximum stored carbon were the goal, the production of timber from the plantation would be reduced.

Such stark, mutually exclusive trade-offs are not inevitable. It is usually possible to get some level of climate service from a landscape without completely compromising other land use objectives. There are even cases of synergy, where management for the climate regulation service is also beneficial for other services. For example, the REDD+ notation suggests that protection of the climate regulation service provided by tropical forests can also confer biodiversity, water, and livelihood benefits.

4.09.7 Conclusions

The climate regulation service provided by terrestrial ecosystems is real and substantial. It occurs through a variety of mechanisms, whose relative importance varies from place to place. The carbon storage mechanism at global scale has increased over the past few decades, largely through autonomous mechanisms (in other words, not as the result of deliberate human actions). The terrestrial carbon sink cannot continue to grow indefinitely. There are several feedback processes, which may cause it, perhaps within decades, to change from a sink at the global scale to a net carbon source, even though at local or regional scale some areas may remain as sinks.

The terrestrial carbon storage service is in general relatively vulnerable, both to climate itself and to associated environmental change factors such as changes in fires, windstorms, and pest outbreaks. It is also vulnerable to economic and political factors, which may or may not be linked to climate. The magnitude of the carbon storage service can be moderately increased at local scale through management actions, and at regional and global scale through policy decisions, but doing so tends to increase the vulnerability of the service. The vulnerability of the service can probably be significantly reduced, but not eliminated through a combination of management and policy actions.

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4.10 Vulnerability of Agroecosystems to Environmental Factors

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4.10.1 Introduction

Earth's climate is moderated by coupled cyclings of carbon (C), nitrogen (N), water (H_2O), phosphorus (P), and sulfur (S). Perturbations of these cycles, by natural or anthropogenic forces, can alter Earth's climate. It is the anthropogenic disturbance of the C and N cycles, through land use and fossil fuel combustion, which has increased the risks of changes in climate statistics. Mitigation of and adaptation to environmental changes necessitate enhanced understanding of the processes, causes, and factors that control vulnerability of an ecosystem to the combined effects of environmental change drivers. Sources and drivers of these changes must be known and prudently managed.

4.10.1.1 Agroecosystems and Sources of Anthropogenic Emissions

There are two principal sources of anthropogenic emissions: land use conversion and fossil fuel combustion. Conversion of natural ecosystems to agricultural land commenced with the dawn of settled agriculture about 10–13 millennia ago. Ruddiman (2002) hypothesized that drastic anthropogenic changes occurred by the onset of forest clearance about 8000 years ago and with cultivation of irrigated rice paddies and domestication of livestock about 5000 years ago. The C flux through land use change from prehistoric times to 2000 has been estimated at 480 Pg by Ruddiman (2003) and 262 Pg by Olofsson and Hickler (2008). The latter estimate was comprised of 114 Pg during the preindustrial time and 148 Pg since the industrial era between 1850 and 1990. Olofsson and Hickler (2008) estimated that 90% of the C emission from land use conversion occurred after AD 1. Between AD 1 and 2000, a large number of natural ecosystems (forests and savannas) have been converted to cropland and pastureland (**Table 1**). Gaseous emissions from combustion of fossil fuel drastically increased between 1750 and 2000. Whereas the contribution of land use to atmospheric C exceeded that of fossil fuel combustion until late 1950s or early 1960s, the relative magnitude of emission by land use has progressively decreased. The data in **Table 2** show that the ratio of CO_2–C emission from fossil fuel combustion (plus cement production): land use was 2.1 in 1960s, 3.6 in 1970s, 3.7 in 1980s, 4.0 in 1990s, 5.5 in 2000s, and 7.3 in 2008. To date, the cumulative amount of CO_2–C emission is about 300 Pg from both land use and fossil fuel combustion (Archer 2009). The anthropogenic transformation of terrestrial biomes has been drastic between 1700 and 2000 AD. In 1700, about 50% of the terrestrial biosphere was wild, and 45% of the remainder was in a seminatural state. By 2000, the majority of the biosphere was under agriculture and urban settlement and <20% was seminatural (Ellis et al. 2010). Increase in human demands, especially the production of food, has been the principal driver of this transformation.

4.10.1.2 Ecosystem Services

Rather than a gradual change to which the ecosystems can adjust, extreme climate events or abrupt climate changes can cause severe disturbance of ecosystem functions and services. Ecosystem services represent the benefits that people (and

Table 1 Trends in global population and land use

			Land area (10^6 ha)	
Era	*Year*	*Population (10^6)*	*Crops*	*Pasture*
BC	10 000	2	0	0
	5000	18	–	–
AD	1	188	130	110
	500	210	120	110
	1100	295	180	170
	1400	350	190	190
	1800	989	420	510
	1900	1654	850	1290
	1950	2545	1210	2470
	2000	6145	1530	3430

Adapted from Goldewijk 2010; Mc Neal 2000; UN Population Statistics 2011.

Table 2 Estimates of CO_2–C emissions by land use and fossil fuel combustion + cement production

	CO_2–C emissions (Pg C/yr)		
Period	*Fossil fuel + cement*	*Land use*	*FF:LU*
1960–70	3.1	1.5	2.07
1970–80	4.7	1.3	3.62
1980–90	5.5	1.5	3.67
1990-2000	6.4	1.6	4.00
2000–08	7.7	1.4	5.50
2008	8.7	1.2	7.25

Adapted from Lé Quéré et al. 2011.

other biota) obtain from ecosystems. The specific benefits vary among ecosystems or biomes. Thus, assessment of these benefits necessitates formulation of indicators that may differ among diverse ecosystems. It is also important to establish baselines (Perrings et al. 2011; Kumar 2010), against which to measure the changes in ecosystem services. The Millennium Assessment (2005) project estimated that 60% of the services or societal benefits provided by biomes have been diminished through human activities since the 1950s. Consequently, the boundaries of natural biomes are being redrawn (Alessa and Chapin 2008) and the drastically altered biomes are called Anthromes. Sustainability of these systems is vulnerable to the multitude of stressors generated by human activities as these affect energy/nutrient transfer along food webs and the cycling of water and elements (i.e., C, N, P, S). These anthromes must now provide the ecosystem services needed to sustain human societies, and crops obviously have a major role in this activity.

Crops are planted to provide 'provisioning services' (see Chapin et al. 2009), but the consequences and potential change in other ecosystem services related to climate (e.g., supporting and regulating services) is equally large. Land use and land cover change is a major player affecting regional climate characteristics (Pielke et al. 2011; Pitman et al. 2011; Avila et al. 2012). Agroecosystems have profound effects on local and regional climates via their ability to alter energy returns to the atmosphere. As noted by Baldochi (this volume), agroecosystems have reflectivity (albedo) values that are often different from native vegetation found in similar areas. Higher albedos can reduce surface warming, and the importance of increasing crop albedos has become a legitimate science question (e.g., Ridgwell et al. 2009). More importantly, crops are usually designed to exploit soil moisture, such that energy captured by evapotranspiration (latent heat) can also be higher than in native vegetation, and with irrigation, the percentage of net radiation that is transferred back to the atmosphere in water vapor can be very high. This water vapor can be returned as rainfall (e.g., Pielke et al. 2007). Thus, agricultural systems have the potential to mitigate surface temperatures and can potentially increase rainfall, particularly if irrigation is applied and mechanisms exist to deliver moist air to the atmosphere. Thus, the extent of agroecosystems across terrestrial surfaces and the specific crop and management scheme used on these lands have large effects on climate and have the potential to be used as a mitigation factor.

Extreme events can lead to changes in ecosystem services (Breshears et al., 2011). For example, drought-induced tree die-off and the increase in risks of fire in semiarid woodlands and grasslands can severely disrupt services provided by these ecosystems. It is widely hypothesized that extreme events exacerbate risks of wild fires (Pederson et al. 2010; Bowman et al. 2009), tropical storms, and the attendant large floods (Overpeck and Cole 2006) such as in Thailand in 2011, droughts (Wilcox 2010), such as in Texas in 2011, tourism and fisheries (Pederson et al. 2010).

The Anthropocene era, through drastic transformation of Earth's biomes and by fossil fuel combustion, has altered the atmospheric chemistry and increased the concentration of greenhouse gases, as well as converted vast regions from their natural landscape type. The current climatic conditions, as a result of these human disturbances, have exacerbated the vulnerability of ecosystems that were already transformed by other anthropogenic activities. Thus, the objective of this chapter is to deliberate the vulnerability of terrestrial agroecosystems to possible changes in the coming decades and to establish the cause–effect relationship between land use and climate.

4.10.2 Food Security

The issue of food security, for the growing and increasingly affluent population, is both the cause and the effect of the anthropogenic activities. It is the ever-increasing human demands for food, feed, fiber, and fuel that are driving the transformation of Earth's biomes and additional need for land to meet these demands (Bruinsma 2009; Clay 2010). There is a need to critically and objectively rethink food security for the 21st century (Falcon and Naylor 2005). In addition to the overview provided here, readers are urged to see the recent volume focusing on climate vulnerabilities of food resources edited by Niyogi (2013).

4.10.2.1 Food Demand

The doubling of agricultural production between 1965 and 2000 by adoption of the Green Revolution technologies was brought about through increases in inputs by 7 times for nitrogenous fertilizers, 3.5 times for phosphatic fertilizers, 1.7 times for the irrigated cropland area, and 1.1 times increase in the arable land area (Tilman 1999). Since 1970, crop production has more than doubled, although cropland area has increased by only 12% (Foley et al. 2007). The nitrogenous fertilizer, produced by the Haber–Bosch process of converting inert atmospheric N_2 into reactive NH_3, has made it possible to feed an additional several billion people. Without these fertilizers, it would take substantially more cropland than 1.5 billion hectares currently used for cultivation. Such large areas simply do not exist. Thus, the projected 70% increase in food production between 2010 and 2050 will necessitate additional use of fertilizer inputs and also some expansion in the arable land area. The long-term chemotherapy of agricultural land, by use of fertilizers and pesticides, has altered both structure and functions of agroecosystems. Soil and climatic measurements indicate that the global annual average surface air temperature has warmed by about 0.8 ± 0.2 °C since 1850 (The Royal Society 2010), and continued increases are a plausible scenario (IPCC 2007). Intensive food production will further aggravate emission of greenhouse gases and drastically alter the terrestrial and aquatic biomes. Anthropogenic emissions, by land use conversion and fossil fuel combustion, are estimated to have increased global temperatures by ~0.13 °C/decade since 1950, with similar increases possible over the next few decades (IPCC 2007; Lobell et al. 2011). As seen to date, local and regional responses, however, will considerably vary. Moreover, a global annual average surface temperature does not capture the actual temperatures experienced across the diverse croplands.

The term food security implies four key dimensions: availability, stability, access, and utilization (FAO 2010). Both current and plausible future climate can adversely affect stability of food supply and its access to vulnerable population because agriculture is not only a source of food but also of the income for small land holders and resource-poor farmers from around the world (Schmidhuber and Tubiello 2007). Direct and indirect effects of climate on food security are outlined in **Figure 1**. The direct effects are those that alter production and may be positive or negative. Whereas the possible negative effects are widely discussed in scientific and popular media, there may as well be some opportunities created by alterations in regional and local climatic conditions that must also be identified and harnessed. The indirect effects are those that may alter food access and stability by changing income, distribution, and post-harvest losses (**Figure 1**). The exact magnitude and direction (positive or negative) are difficult to generalize. Through adaptive and coping strategies, discussed in Section 4.10.4, the goal is to accentuate the positive and minimize the adverse or negative effects.

More than one billion people are vulnerable to food insecurity (Barrett 2010), and the number may increase because of the possible decrease in cropland area by 110 million hectares (Mha) in developing countries located in the lower latitudes (Schmidhuber and Tubiello 2007). Shifts in the growing season may lead to declines in the land area suitable for double cropping in some areas but could increase this potential elsewhere. In addition, water limitation and droughts strongly reduce crop yields and livestock productivity. Vulnerability to climate-induced food insecurity may be more severe for small land holders who practice subsistence agriculture (Morton 2007). It is defined as "farming and associated activities which together form a livelihood strategy where the main output is consumed directly, where there are few if any purchased inputs, and where only a minor proportion of output is marketed" (Barnett 1997). Similarly, small-holder agriculture refers to "rural producers who farm mostly by family labor and for whom farming is the principal income source" (Cornish 1998). Despite numerous constraints, subsistence and small land holders have inherent advantages to cope with a subset of climate-induced stresses. Important among these advantages are high labor efficiency, large livelihood diversity, and benefits of indigenous knowledge (Morton 2007). These characteristics have evolved over generations and, thus, have high adaptability and built-in coping strategies toward climate variability and other biotic and abiotic stresses.

Drought-related adverse effects of climate on food-security are also caused by excessive heat during the growing season (Battisti and Naylor 2009). The crop yield gap, the difference in

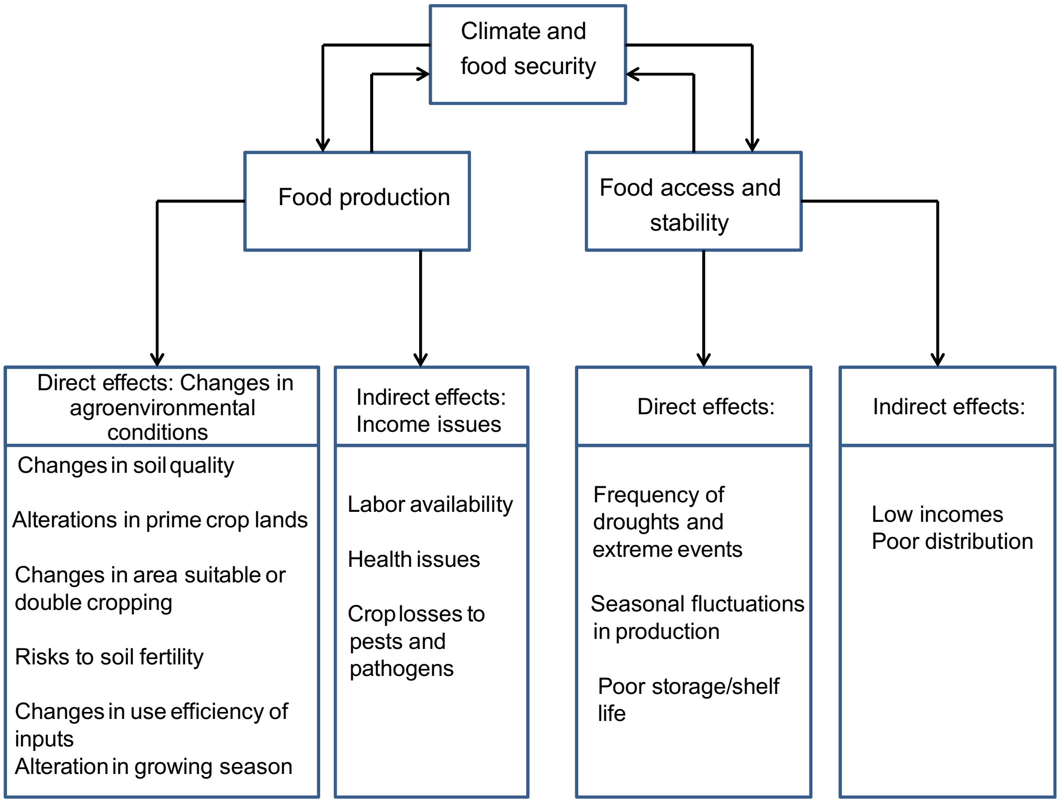
Climate and food security
Food production
Food access and stability
Direct effects: Changes in agroenvironmental conditions
Changes in soil quality
Alterations in prime crop lands
Changes in area suitable or double cropping
Risks to soil fertility
Changes in use efficiency of inputs
Alteration in growing season
Indirect effects: Income issues
Labor availability
Health issues
Crop losses to pests and pathogens
Direct effects:
Frequency of droughts and extreme events
Seasonal fluctuations in production
Poor storage/shelf life
Indirect effects:
Low incomes
Poor distribution

Figure 1 Direct and indirect effects of climate on food security.

Table 3 Existing yield gap for principal food crops in developing countries

		Yield gap	
Crop	*Country/region*	*Mg (yr^{-1})*	*Average yield (%)*
Wheat	Mexico-Yaqui Valley	5.8	41
Wheat	Bangledesh	2.9	45
Wheat	Northern India	4.5	150
Rice	India	2.3	64
Rice	China	5.9	29
Rice	Indonesia	5.3	21
Rice	Thailand	4.0	32
Rice	Philippines	3.4	85
Maize	South Asia	1.4	690
Maize	Sub-Saharan Africa	0.7	543
Maize	Latin America Highlands	4.0	150

% Gap = [(potential yield – average yield)/average yield] × 100.
Adapted from Lobell, D. B., K. G. Cassman, and C. B. Field, 2009: Crop yield gaps: their importance, magnitudes and causes. *Annu. Rev. Environ. Resour.*, **34**, 179–204.

attainability, and the national average crop yield (Hengsdijk and Langeveld 2009; Lobell et al. 2009) are large for subsistence and small land holders of developing countries (Tables 3 and 4). For example, the yield gap (%) for wheat is 150 in northern India and 41 in Yaqui Valley, Mexico, that for rice is 64 in India and 21 in Indonesia, and that for maize is 690 in South Asia and 150 in Latin America (Table 3). The yield gap (%) for rice is 13 in Northeast Asia and 575 in humid Arica, that for maize is 7 in western Europe and 506 in humid Africa, and that for tropical cereals is 867 in South Asia and 986 in semiarid Africa (Table 4). The yield gap has been more highly influenced than has been the climatological average temperatures during the growing season, and by any increase in drought and other extreme events. Indeed, the climate is a severe threat to global food security.

4.10.2.2 Required Crop Yield in Developing Countries to Meet the Food Demand

Much of the food production growth between 2010 and 2050 must come from increase in productivity per unit area and use efficiency of inputs. Some inputs essential to enhancing productivity of grain crops include fertilizers and irrigation. Based on all inputs involved, the required yields of three food crop staples must be increased in all developing countries between 2005–07 and 2050 by as much as 60% for wheat, 49% for rice, and 55% for maize (Table 5). With large footprints for irrigation and the associated energy requirements (Khan and Hanjara, 2009) along with threats to human water security (Vörösmarty et al. 2010), supplemental irrigation is a major uncertainty for many areas. The projected slow trend in cereal yields increase in developing countries from 1961–63 to 2050 range from 2.2 to 0.8%/yr (Bruinsma 2009). Thus, the importance of irrigated agriculture in moderating the yield increase cannot be overemphasized. There has to be a rising share of increase in yield through irrigation, especially in China, India, and other developing countries. The data in Table 6 indicate the required increase in yield of cereals in the world and in developing countries with and without irrigation. By 2050, it is estimated that grain yield of all rainfed cereals would have to be increased from 2.64 to 3.58 Mg ha^{-1} in the world and 1.97–2.80 Mg ha^{-1} in the developing countries. Thus, the total increase in rainfed cereal yield, in this scenario, would be ~36% for the world and ~42% for the developing countries. In comparison, the cereal yield of irrigated agriculture would be increased from 4.67 to 6.10 Mg ha^{-1} (31%) in the world compared with 4.39–5.90 Mg yr^{-1} (34%) in the developing countries. In comparison with the rainfed conditions, cereal yield with irrigation in the world and developing countries, respectively, was 76% and 123% in 2005–07 compared with the scenario increase of 70% and 111% by 2050. Moderate alterations in regional and local climatic conditions may also have some beneficial impacts in some regions across East Africa (Doherty et al. 2010).

4.10.2.3 Vulnerability of Cropland to Extreme Events

Climate can impact cropland by altering the risks to soil degradation and desertification (Geist and Lambin 2004) and the resilience of land that is potentially cultivable. Erosion is a major long-term threat to soil fertility and agriculture regardless of the presence of other drivers of soil change (Montgomery 2007). The risks of soil degradation by erosion (water and wind), salinization, and other processes may be exacerbated by extreme events (e.g., fire, drought, floods) and other climate related factors (Feddema and Freire 2001). Reduction in the vegetative cover by fire and the hydrophobic surface conditions thus created are known to cause flash floods and increase risks

Table 4 Yield gap of principal crops on regional basis

	Maize		*Rice*		*Tropical cereals*	
Region	*AY (Mg ha^{-1})*	*Gap (%)*	*AY (Mg ha^{-1})*	*Gap (%)*	*AY (Mg ha^{-1})*	*Gap (%)*
Caribbean/LA	3.5	186				
Africa-semi-arid	3.0	237			0.7	986
Africa-humid	1.6	506	1.6	575	1.5	467
Europe-western	9.0	7				
Asia-South	2.1	457	3.3	173	0.9	867
Asia-Northeast			6.3	13		
Asia-Southeast			3.9	154		

AY = average yield. Gap (%) = (yield gap/average yield) × 100.
Adapted from Hengsdijk, H., and J. W. A. Langeveld, 2009: Yield Trends and Yield Gap Analysis of Major Crops in the World. Wettelijke Onderzoekstaken Natuur & Milieu, 59 pp.

Table 5 Past and required crop yields in developing countries including estimates for 2050

	Yield (Mg ha^{-1})		
Crop	*1961–63*	*2005–07*	*2050*
Wheat	0.98 (1.48)	2.35 (2.85)	3.77 (3.60)
Rice	1.90 (2.19)	3.70 (3.74)	5.15 (5.33)
Maize	1.07 (1.47)	2.49 (3.77)	3.87 (4.40)

Numbers in parenthesis are the world average yields.
Adapted from Bruinsma, J., 2009: The Resources Outlook to 2050: By How Much do Land, Water, and Crop yields Need to Increase by 2050? FAO, Economic and Social Development Department, 33 pp.

Table 6 Role of irrigation in achieving the required increase in cereal grain yields in the world and in developing countries, including estimates for 2050

		2005–07 Yields (Mg ha^{-1})		*2050 Yields (Mg ha^{-1})*	
Crop	*Irrigation*	*World*	*Developing countries*	*World*	*Developing countries*
Wheat	Rainfed	2.37	1.67	3.17	2.57
	Irrigated	3.50	3.41	5.08	5.06
Rice	Rainfed	2.54	2.54	3.26	3.26
	Irrigated	5.10	5.04	6.40	6.37
Maize	Rainfed	4.26	2.70	5.58	3.69
	Irrigated	6.74	5.27	7.43	6.53
All Cereals	Rainfed	2.64	1.97	3.58	2.80
	Irrigated	4.67	4.39	6.10	5.90

Adapted from Bruinsma, J., 2009: The Resources Outlook to 2050: By How Much do Land, Water, and Crop yields Need to Increase by 2050? FAO, Economic and Social Development Department, 33 pp.

of surface runoff and accelerated erosion (Gimeno-Garcia et al. 2007). Removal of vegetation cover, such as by overgrazing (Otterman 1974) or by inappropriate cropping management, can expose high-albedo subsoil and enhance vulnerability to desertification.

There is an estimated reserve of about 120 Mha of potentially cultivable land mainly in tropical South America and Africa. There may be a decrease in the suitability of these lands for cropland by climate shifts (Ramankutty et al. 2002). In contrast, however, there might be an expansion in cropland suitability in the northern hemisphere and high latitudes.

4.10.2.4 Carbon Sequestration in Agroecosystems and Soil Quality

Soils of agroecosystems (i.e., croplands, grazing lands) have a potential to sequester carbon (Lal 2004; 2010a) and offset anthropogenic emissions. However, surface temperature increases may alter the metabolic balance of agroecosystems, disturb the dynamic equilibrium between photosynthesis and respiration, and reduce the rate and magnitude of C sequestration in soil and the biomass. There exists a strong positive feedback between temperature and CO_2 emission due to an increase in rate of soil respiration (Melillo et al. 2002; Canadell et al. 2007; Arnone et al. 2008). Soil carbon sequestration is extremely sensitive to temperature regime (Davidson and Janssens 2006). While reducing the soil carbon pool, warming may also adversely impact soil quality and use efficiency of agroecosystems (Lal 2010b). The type of crop and how it is managed can have very large effects on surface temperatures and, therefore, be used to mitigate carbon sequestration (Lal 2008).

4.10.3 Water Security

Climate impacts water resources both directly and indirectly (Brian et al. 2004). Directly, it involves the amount type, timing and distribution of precipitation, and the frequency of extreme events. The direct effects are manifested through base flow, storm flow, flooding, and ground water recharge, as was the case in Texas during 2011. Changes in frequency and intensity of drought can adversely impact the water security including the availability of drinking water. The indirect effects of a temperature increase caused by land use changes (e.g., Fall et al. 2009), or other climate effects, on water security are partly due to the fertilization effect from CO_2 (especially in C_3 plants) and partly due to increase in plant water use because of increase in temperature. The latter increases both transpiration and evaporation, thereby decreasing the stream flow and the aquifer recharge. The combined direct and indirect effects, as influenced by nitrogen deposition and additional factors, may also alter the species composition over the long term (Sun et al. 2011).

Water security also depends on the ground water resources, which can be altered by the changes in precipitation. About 75% of the residents of European Union depend on ground water for their water needs (Klove et al. 2011). Irrigation of the rice-wheat system in the Indo-Gangetic Plains of South Asia also depends on the ground water. An important threat to the supply of ground water is through depletion (lowering) of the water table because of excessive withdrawal and lower recharge. This threat is driven both by human decisions as well as by climate. Environmental changes collectively alter the components of the hydrologic cycle (i.e., surface, runoff, base flow, soil water storage, evapotranspiration) and affect water security especially in arid and semiarid regions.

Changes in the hydrologic cycle can affect the river flow (Palmer et al. 2009) and thus affect water security. There is a strong link between food security and the availability of renewable fresh water resources. Reduced availability of good quality water for irrigating croplands that produce 40% of the world's food on just 18% of the irrigated area (Khan et al. 2009) is an example of the close link between food security and water security. Almost 80% of the world population is vulnerable to high levels of threat to water scarcity (Vörösmarty et al. 2010), and the threat is likely to be exacerbated in the future (Karl et al. 2009).

4.10.4 Adaptation of Agroecosystems to Climate

Principal ecosystem services provided by agroecosystems are food, feed, fiber, and fuel. Food security (see Section 4.10.2) will remain a major global issue until 2050 and beyond. The challenge of food security for 9.2 billion people by 2050 is enhanced by consumption growth and climate uncertainties. The increase in animal-based diet with an increase in per capita income may also aggravate the food insecurity (Keyzer et al. 2005). Lobell et al. (2011) estimated that between 1980 and 2008, global maize and wheat production declined by 3.8 and 5.5%, respectively, because of the change climate experienced during this time interval. Crop yield may also be reduced by increase in risks of soil erosion and the attendant loss of soil C that would also jeopardize soil quality (Ito 2007). The competition for land between production of food and biofuels may also aggravate food security (Raghu et al. 2011). Expansion of agroecosystems, conversion of natural biomes to croplands, and pasturelands would have profound effect on biodiversity and other ecosystem services (Green et al. 2005). However, agroecosystems can be managed to both mitigate and adapt to the spectrum of plausible future regional and local climates.

Agricultural ecosystems, already occupying 40–50% of the Earth's land surface, can be important and cost-effective soil C sinks. Thus, an active management toward recarbonization of the biosphere is an important option to affect future atmospheric CO_2 levels (Obersteiner et al. 2010). Important among these options for agroecosystems are restoring and reclaiming eroded and degraded soils and ecosystems, increasing soil C pool, conserving soil and water, and adopting farming systems that have high use efficiency of inputs. Considering all gases, the global technical mitigation potential (i.e., the removal of atmospheric CO_2) of agroecosystems by 2030 is estimated to be 0.4–0.44 Pg C/yr at C price \$20/Mg CO_2, 0.68–0.74 Pg C/yr at C prices of \$50/Mg CO_2, and 1.09–1.1 Pg C/yr at C price of \$100/Mg CO_2 (Smith 2011). These options are truly a win–win because of numerous cobenefits and deserve to be subjects of continued discussion.

In the context of adaptation, agriculture can be either based on the strategy of sustainable intensification by adopting land-saving technologies or it can be a nature-friendly system. Should agriculture be done to manage biodiversity or should biodiversity be preserved/protected through management of agriculture? There can be a trade-off between these two options (Green et al. 2005). Can 'climate-smart' agriculture advance food security and improve the environment (Pearce 2011). In the context of small land holders and subsistence farmers, adaptive and coping strategies are outlined in **Figure 2**. Sustainable management of soil and biophysical resources through adoption of recommended management practices (RMPs) is one option. Efficient management of labor and human resources through addressing the human dimensions is another (**Figure 2**). Both options are important to advancing food security and may differ among regions with different biophysical and social/economic/cultural factors.

It is generally argued that South Asia and Sub-Saharan Africa are two regions that may be prone to negative effects on food security without sufficient adaptation of appropriate measures (Lobell et al. 2008). However, the uncertainties about crop failure and severe yield reductions widely vary among crops, soils, and agroecoregions. While improving short-term options is important, it is also necessary to identify and implement long-term strategies that may include the following (Fazey et al. 2010): (a) addressing both the biophysical and the

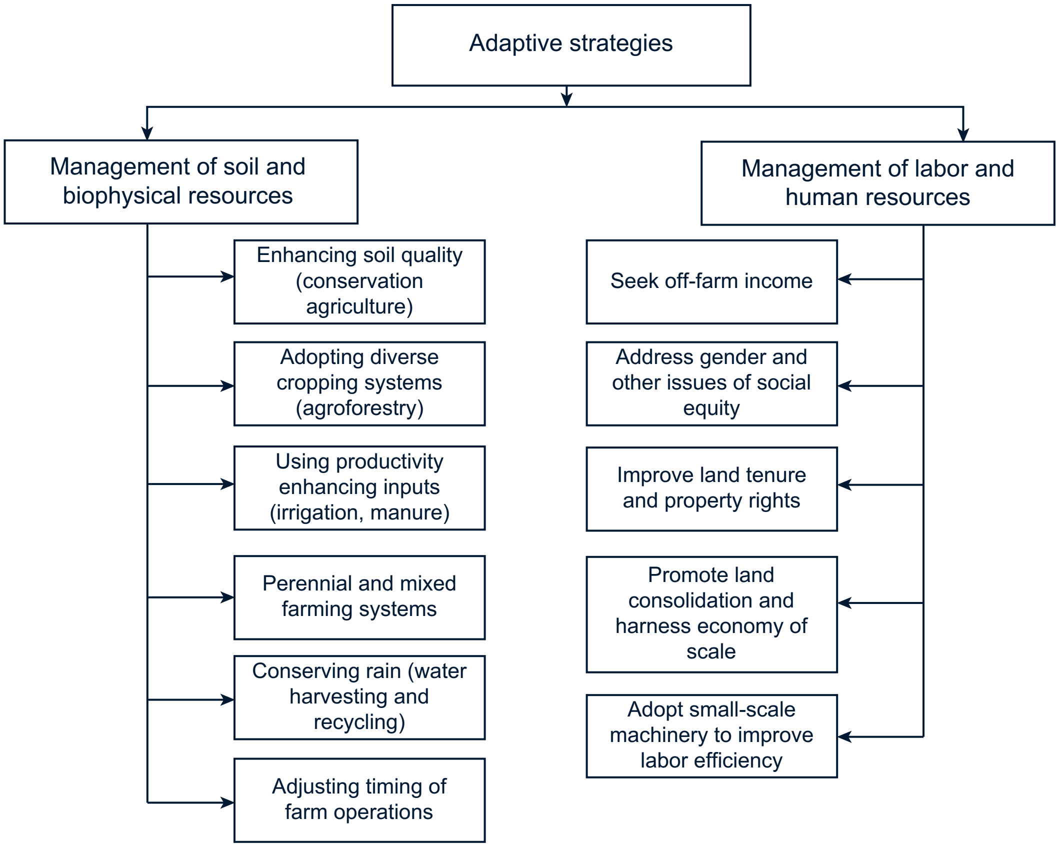
Adaptive strategies
Management of soil and biophysical resources
Enhancing soil quality (conservation agriculture)
Adopting diverse cropping systems (agroforestry)
Using productivity enhancing inputs (irrigation, manure)
Perennial and mixed farming systems
Conserving rain (water harvesting and recycling)
Adjusting timing of farm operations
Management of labor and human resources
Seek off-farm income
Address gender and other issues of social equity
Improve land tenure and property rights
Promote land consolidation and harness economy of scale
Adopt small-scale machinery to improve labor efficiency

Figure 2 Adaptive and coping strategies by small land holders and subsistence farmers.

human dimensions (refer to Figures 1 and 2), (b) diversifying the adaptive and coping strategies, (c) strengthening human resources capacity to enable the adoption of required strategies, and (d) putting biofuels in the ecosystem services context (Gasparatos et al. 2011).

4.10.5 Policy Implications for Agriculture

For what are perceived as the most vulnerable regions due to a variety of physical and social stressors (i.e., South Asia and Sub-Saharan Africa), community-driven development may be an appropriate option (Agrawal et al. 2008). This option would entail involvement of local institutions comprising civic, public, and private organizations. These institutions are relevant to gathering and disseminating relevant information, resource mobilization and allocation, capacity building, networking, and providing leadership. Promotion of RMPs as adaptive and coping strategies can be enhanced and facilitated through payments for environmental or ecosystem services (PES). Important among these are increasing C sequestration in soils and biota, improving water quality and supply of renewable freshwater resources, enhancing biodiversity, etc. While not being a panacea, PES is an important strategy of incentivizing the land managers and farmers toward adoption of a restorative land use and RMPs (Wertz-Kanounnikoff et al. 2011). The strategy of PES can be effective in situations where RMPs have numerous cobenefits, land managers are direct beneficiaries, and there exists a strong support from community and local institutions. Such actions are warranted regardless of climate concerns, but their solutions include ways to mitigate potential climate issues as well.

4.10.6 Conclusions

The disturbance of the global carbon, water, and nitrogen cycles through land use and fossil fuel combustion can strongly impact both natural and managed ecosystems. Impacts of climate in the coming decades, both positive and negative, depend on the specific ecosystem and the biophysical, social, economic, political, and cultural parameters. Warming, drying, and an increase of extreme weather events are examples of possible changes in regional and local climate statistics that could reduce food security, water security, and biodiversity and exacerbate soil degradation and desertification. These negative effects are exacerbated by the human dimensions such as population density, human resources capacity, local institutions, and political governance. Agroecosystems, covering 40–50% of Earth's land area, have the potential to both mitigate and adapt to climate. The mitigation potential exists through a large carbon sink capacity in soil and biomass, as well as the feedbacks produced by the crops' ability to alter reflectivity, change the fraction of heat transferred into the atmosphere by sensible and latent heat flux, and energy capture. The carbon sink capacity as well as energy mitigation can be realized through conversion to a judicious land use, restoration of degraded soils and desertified ecosystems, and adoption of recommended practices for soil, water, crops/plants, and animals management. Promotion of adaptive and coping strategies can be facilitated through payments for ecosystem services and adoption of climate-resilient agriculture. In this regard, the importance of local institutions and community involvement cannot be overemphasized. Recarbonization of the terrestrial biosphere is a win–win option because of its numerous cobenefits and cost-effectiveness of the natural process.

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4.11 Vulnerability of Pollination Ecosystem Services

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Glossary

Bridging plants Plants utilized in habitat restorations to provide resources for pollinators during resource-poor time periods.

Ecosystem services A set of resources and processes provided by ecosystems that contribute to human well-being.

Food security The availability and access to sufficient, safe, and nutritious food for a community or individual.

Framework plants Plants utilized in habitat restorations to provide resources necessary for supporting large numbers of pollinator species or individuals.

Phenology Plant and animal life cycle events that are often periodic and usually influenced by seasonal variations in climate.

Pollination The process by which pollen is transferred from anthers to stigma, initiating sexual reproduction and formation of the fertilized fruit or seed.

Pollinator networks A visual display of plant–pollinator interactions, usually based on visitation or pollen-load data.

Pollinator network connectance The proportion of plant–pollinator links observed in a network (links/species).

Pollinator network nestedness Where specialists interact with subsets of species with which generalists also interact, creating a 'nested' structure.

Perhaps one of the most critical yet understudied factors affecting the decline of global pollinator populations and pollination services are alterations in local and regional climatic conditions. In the past few decades, humans have significantly altered climatic conditions due to the emissions of aerosols, and of greenhouse gases, including CO_2, and from land management practices (NRC 2005) consequently impacting wild species distributions and population dynamics across the world (reviewed by IPCC 2001; Parmesan 2007; Parmesan and Yohe 2003). Because most pollinators are completely reliant on plants for food resources, pollinator populations maybe both indirectly affected by changes in the abundance, spatial distribution, and timing of flowering in plant populations, and directly affected by the climate of the regions in which they occur. Thus, the discussion of climate impacts on pollination services requires an analysis of both direct and indirect interactions between climate, plants, pollinators, and the many threats to plant and pollinator populations (**Figure 1**).

In this chapter, we review scientific literature surrounding four key topics: (1) the ecological interactions related to pollination services and vulnerability, (2) the ecosystem services provided by native pollinators and their potential alteration, (3) mitigation possibilities for improved pollination acquisition, and (4) the resulting policy implications (**Figure 1**). Given the large scope of this topic, we focus on insect pollinators, which are one of many pollinator groups

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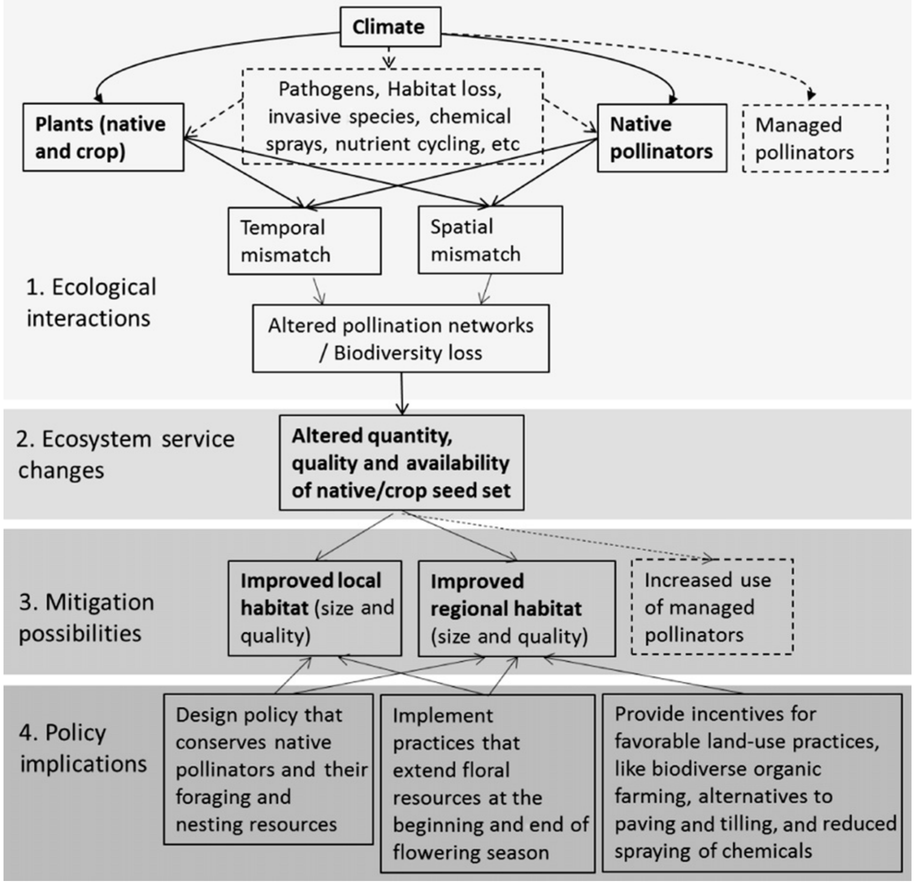
Climate
Pathogens, Habitat loss, invasive species, chemical sprays, nutrient cycling, etc
Plants (native and crop)
Native pollinators
Managed pollinators
Temporal mismatch
Spatial mismatch
1. Ecological interactions
Altered pollination networks / Biodiversity loss
2. Ecosystem service changes
Altered quantity, quality and availability of native/crop seed set
3. Mitigation possibilities
Improved local habitat (size and quality)
Improved regional habitat (size and quality)
Increased use of managed pollinators
4. Policy implications
Design policy that conserves native pollinators and their foraging and nesting resources
Implement practices that extend floral resources at the beginning and end of flowering season
Provide incentives for favorable land-use practices, like biodiverse organic farming, alternatives to paving and tilling, and reduced spraying of chemicals

Figure 1 Framework showing how climate influences plants and pollinators, and thus the availability and quality of ecosystem services. Part 1 of the figure is adapted from Hegland, S. J., A. Nielsen, A. Lazaro, A. L. Bjerknes, and O. Totland, 2009: How does climate warming affect plant-pollinator interactions? Ecol. Lett., 12, 184–195, and the remaining parts indicate the change in ecosystem services and role of management practices and policies on pollination services, respectively. Dashed lines and arrows indicate areas not covered by this review.

(e.g., birds, mammals), but are the most economically important pollinator groups globally (Roubik 1995; Winfree et al. 2011a). Because very little literature is available on the direct impacts of climate on pathogens, chemical sprays, and other threats to pollinators, we only speculate on these topics and advise that greater research is required for an understanding of these factors. Because one of the objectives of this review is to provide ecologically informed management suggestions for improved pollination services, we focus on native pollinators, which have the potential to provide sustained pollination services. Compared to the services provided by a single species of managed pollinator (e.g., the honey bee), species-rich communities of wild pollinators can provide redundancy in terms of pollinator services (Kremen et al. 2004) and thus may provide services that are more stable over time (Garibaldi et al. 2011) and in the face of environmental change. However, we suggest that climate impacts on managed pollinator communities are topics of great importance and require further study. Overall, by summarizing the literature relevant to climate impacts on native pollinators, we provide generalizable and ecologically informed management suggestions for scientists and policy makers across communities and ecoregions.

4.11.1 Ecological Interactions

4.11.1.1 Pollination Services

Ecosystem services are the set of ecosystem functions that contribute to human well-being and include provisioning, supporting, regulating, and cultural services (Daily 1997; Millenium Ecosystem Assessment 2005). Pollination of plants by animals is both a regulating and a supporting ecosystem service. As a regulating service, it is essential for the reproduction of pollinator-dependent plants that supply humans with foods, fiber, forage, biofuels, firewood, timber, and medicine. The contributions of pollination services to human well-being may be direct or indirect. Direct contributions include fruit or seed production of pollinator-dependent food, fiber, biofuel, and forage crops (e.g., alfalfa, apple, blueberry, canola, cherry, cucumber, cotton, longan, macadamia, melon, raspberry, squash, soy, and sunflower). Indirect contributions of animal pollination include the reproduction of tree species valued for timber (e.g., mahogany, White et al. 2002), sown crops in which the vegetative parts are eaten, seed production (e.g., lettuce, broccoli, carrot), vegetatively propagated crops in which animal pollinators are required for breeding only (e.g., potatoes, banana), and pollinator-dependent plants with medicinal properties [e.g., *Catharanthus* spp., which include the famous Madagascar periwinkle (reviewed in Klein et al. 2007; Miyajima 2004)]. As a supporting service, pollination is essential to maintain populations of pollinator-dependent wild plants (Aguilar et al. 2006) that then provide additional ecosystem services, such as erosion control, water filtration, carbon storage, and habitat for biodiversity (discussed in greater detail in the following sections, reviewed in Kremen et al. 2007).

Of these various contributions to human well-being, scientists have to date only rigorously quantified importance of pollination services to food crop production (e.g., effects of animal pollination on fruit and seed yield, and on seed production for crops in which vegetative parts are eaten). These studies have shown that 75% of all crop species depend on animal pollinators to produce fruits or seeds, either partially or completely, supplying 35% of global crop biomass (Klein et al. 2007). Importantly, these crops also supply the majority of certain essential micronutrients in plant-based food, such as dietary lipid (74%), vitamins A (70%), C (98%), E (35–66% of tocopherols) and folate (55%), and minerals calcium (58%) and fluoride (62%) (Eilers et al. 2011). Since some crop production from animal-pollinated crops is due to self or wind pollination, the total amounts of biomass and micronutrients due to yield increases from animal pollination will be less than these numbers, but remain substantial (Eilers et al. 2011; Klein et al. 2007). Worldwide, the pollination services for food crop production, including both those provided by managed bees imported to crop fields and those freely provided by wild bees, were recently valued at €153 billion/year (prices from year 2005), 9.5% of global crop value (Gallai et al. 2009).

Neither the micronutrient nor the economic calculations include the contributions of vegetative crops for which animal pollinators are needed for seed production or breeding. We also lack recent quantitative analyses of the indirect contributions of pollinators to meat and dairy production via forage production (e.g., alfalfa, McGregor 1976), as well as, any calculations of pollinator contributions to fibers, medicinals, botanicals, firewood, timber, and other useful plant species, both cultivated and wild. As 87% of wild plants are pollinator dependent (Ollerton et al. 2011), these contributions are likely to be large.

We can conclude that the contributions of pollinators to human well-being are many and varied. To the extent that wild pollinator species provide these services, then growers do not have to pay beekeepers to supply them, reducing input costs for growers, as well as, food prices for consumers (Chaplin-Kramer et al. 2011; Winfree et al. 2011b). Wild pollinator species still provide sufficient pollination services in certain regions (e.g., Winfree et al. 2007b; Winfree et al. 2008) or in favorable environments within regions (e.g., Garibaldi et al. 2011; Kremen et al. 2002), but in general, with the intensification of agriculture and the loss of natural habitats, both the magnitude and stability of wild pollinator richness, visitation rates, and pollination services have declined in landscapes around the world (Garibaldi et al. 2011). In fact, these declines in pollination services occurred despite no observed declines with intensification in the abundances of the honey bee, *Apis mellifera*, a managed species which growers frequently import to their fields for pollination services.

Declines in the abundance and richness of wild pollinator populations are therefore already having subtle consequences for the human food supply, although these are largely masked by the presence of managed honey bees (Garibaldi et al. 2011). Such effects may intensify as managed honey bees have suffered dramatic declines in some regions (Neumann and Carreck 2010), probably due to synergistic effects of disease, environmental stress, and pesticides (Potts et al. 2010), and wild pollinators are also declining, especially in intensive agricultural landscapes (Garibaldi et al. 2011; Winfree et al. 2009). Declines in wild pollinators will also have large consequences for the reproduction of wild plant populations (Aguilar et al. 2006) that are likely to ramify in their effects on food chains and ecosystem services, potentially affecting both wildlife and humans.

What are the major factors causing wild pollinator declines? Several recent synthetic analyses focusing on bees, the principal pollinators of most crops and many wild plant species, note the loss or degradation of habitat as the principal factor in declining richness and/or abundance (Bommarco et al. 2010; Williams et al. 2010; Winfree et al. 2009). At the landscape scale, meta-analysis showed that pollinator richness and abundance were significantly affected by extreme habitat loss or simplification, but not by moderate habitat loss (54 studies, Winfree et al. 2009); conversely, favorable management practices in farming or grassland landscapes (such as organic farming or set-asides on farmlands or grazing intensity for grasslands) had significant positive effects on abundance and richness of pollinators only in simplified (<20% of non-crop habitats), but not complex landscapes (46 studies, Batary et al. 2011). Guild characteristics affected the response of bees to different habitat disturbance types, as shown in a quantitative synthesis of 19 studies including over 600 bee species; in particular, above-ground nesters and social species were more sensitive to various types of disturbances than below-ground nesters and solitary species (Williams et al. 2010). Social species were negatively affected by pesticide use, but this factor was not significant overall or for other guilds (Williams et al. 2010). Additionally, a few recent studies have shown that pesticide application can have negative impacts on native bee species abundance and richness (Tuell and Isaacs 2010), and declines occur at both local and landscape scales and are more likely to occur after multiple applications (Brittain et al. 2010). However, very little is currently known about the complexities of pesticide impacts on wild pollinators and further research is required to understand the influence of specific pesticide application techniques and chemicals on pollinator life history and behavior in the field.

4.11.1.2 Sensitivity/Vulnerability of Pollination Services

4.11.1.2.1 Temporal Mismatch

Our understanding of the effects of climate on pollination services is weak, in part because determining individual plant and pollinator responses to climate is a vast task, and scaling those responses up to the community level is challenging, given the complexity of such interactions. Pollinator visitation to plants is a community-level phenomenon—merely knowing the species present does not necessarily indicate how they will interact to provide pollination services. In particular, behavioral changes in pollinator foraging may play an important role (e.g., Greenleaf and Kremen 2006) in determining the effects of climate on pollination services. Climate may cause changes in the quality, quantity, and timing of floral rewards in space, and pollinator behavioral responses to those changes are difficult to predict. Furthermore, pollinator behavior is layered on top of changes in pollinator timing and abundance in space. We may begin to piece together potential effects of climate on pollination by considering evidence for each of these pieces separately. To determine the sensitivity and vulnerability of pollination services to climate, we will first review what is known about how plants and pollinators themselves are being affected. (Much of this work has been reviewed previously by Burkle and Alarcon (2011) and Hegland et al. (2009).)

Although the phenologies of some insect pollinators and many plant species have been shown to be affected by warming, few studies have found temporal mismatches in plant–pollinator interactions. Honey bees, bumble bees, and some butterflies are active earlier with warmer temperatures (e.g., Dennis and Sparks 2007; Gordo and Sanz 2006; Sparks et al. 2010) and many plant species are flowering earlier with warmer temperatures, as well (e.g., Amano et al. 2010; Fitter and Fitter 2002; Miller-Rushing and Primack 2008; Sparks et al. 2000). The majority of reported phenological changes for plants and pollinators show advanced activity, yet some show delayed phenology (e.g., Doi et al. 2008; Von Holle et al. 2010), illustrating the need for detailed, and possibly species specific, investigations of different systems before generalizations can be made. In addition, variability in early-season phenologies of plants, and to a lesser degree, butterflies, is increasing (Menzel et al. 2006). When flowering phenologies were experimentally advanced and plants were placed in an unmanipulated community (e.g., the phenologies of pollinators were allowed to unfold naturally), few mismatches were observed (Rafferty and Ives 2011). By resampling and comparing plant–pollinator phenologies and interactions with historical phenologies and interactions, it is possible to test the degree to which interactions are being disrupted by phenological changes. In a comparison spanning 120 years, few mismatches in plant–pollinator interactions directly attributable to phenological change were found (Burkle et al. in prep). These empirical investigations, though limited in number, suggest that temporal mismatches may not play as large a role in decoupling plant–pollinator interactions as previously indicated by models (Hegland et al. 2009; Memmott et al. 2007).

Despite the lack of evidence for widespread temporal mismatches, given the current degree of changes in climatic conditions in some regions, there are likely some cases in which mismatches have led to declines or extirpations of plant and/or pollinator populations. Demographic consequences of such temporal mismatches, however, are not well understood. Thomson (2010) showed strong direct effects of frost events and snowmelt patterns on the reproduction of glacier lilies. Temporal mismatches of glacier lily flowering and the activity of their pollinators may also limit seed set, though this has not been investigated explicitly. Burkle et al. (in prep) have observed the extirpation of half of the bee species historically present in mid-western US forests, though the cause of this bee decline, involving many specialist bees, may not be solely due to temporal mismatches (see below). Effects of climate on pollinator nesting habits and reproduction are largely unknown and have been identified as an important gap in our understanding (Burkle et al. 2011). Miller-Rushing et al. (2010) outlined a way to better understand the demographic effects of phenological mismatches, including key questions and approaches using experiments, models, and long-term data.

4.11.1.2.2 Spatial Mismatch

In addition to temporal mismatches influencing pollination services due to phenological changes in plant and pollinator activity, spatial mismatches may also be as, or more, important. Spatial mismatches between plants and pollinators may occur due to range shifts resulting from climate changes, or due to indirect climate change effects such as habitat destruction and fragmentation. For example, under different climate scenarios, it is possible that humans may use land differently, by altering existing urbanization, development, and/or crop planting patterns, and thus potentially destroying and fragmenting existing habitat. Second, climate can determine the distribution of many plant species, and thus, climate changes can result in spatial shifts in plant populations. Much of the empirical support for range shifts has been performed along elevational gradients in the alpine, where the upward movement of species with warming is relatively straightforward to detect. Plant distributions along elevational gradients can change rapidly with climate, and have been documented as shifting upward in elevation an average of 22 m per decade in the southwestern United States (Kelly and Goulden 2008) and 29 m per decade in western Europe (Lenoir et al. 2008; Walther et al. 2005, 2002). Other studies focused specifically on flowering forbs and their range shifts find similar changes in elevation (Crimmins et al. 2009). In a cross-study comparison, Parmesan and Yohe (2003) found many species, including alpine herbs, to be shifting poleward at an average rate of 6.1 km per decade. In some systems, involving narrowly distributed endemic plants, range shifts may not be possible and declines in species richness have been observed (Damschen et al. 2010). At the other end of the spectrum, some plant species, such as invaders, may adapt and evolve to occupy new environmental conditions associated with climate change, expanding into novel ranges (Gallagher et al. 2010). However, there is also evidence for lack of plant response to recent warming in the alpine, with clones of long-lived plants remaining in the same locations over thousands of years (Bahn and Korner 2003; Steinger et al. 1996). Sherrer and Korner (2010) argue that high microclimatic variation in the alpine would allow plants to ‘escape’ larger scale changes in climatic conditions without moving more than a few meters. Determining which plant species would shift their ranges due to warming and the direction and magnitude of their responses remains challenging.

Few studies have documented range shifts in pollinator species, primarily because knowledge of historic and current distributions are lacking. There are initiatives to map historic pollinator distributions based on museum specimens for comparison to current ranges (Koch in prep). In a few studies, butterfly range shifts have been documented to be moving poleward due to climate changes (Bryant et al. 1997; Kerr 2001; Parmesan and Yohe 2003). Changes in pollinator species distributions are more easily attributed to habitat loss or fragmentation directly (Cane 2001), though the ultimate causes of habitat change may be related to climate shifts and associated changes in human land use. At a local scale of kilometers, loss of historically occurring plant–pollinator interactions can be due to spatial uncoupling in which plants become separated from their pollinating partners in isolated forest fragments (Burkle et al. in prep).

4.11.1.2.3 Alteration of Pollinator Networks

A relatively new method for understanding plant and pollinator interactions at the community level is via the construction of interaction networks (Memmott 1999; Memmott et al. 2004; reviewed in Vazquez et al. 2009). In these networks, single lines connecting plants and pollinators indicate the existence of interactions between two species, making it easier to visualize and analyze changes in these interactions. Examined as a whole, the pollinator network can also convey critical information regarding the structure and function of community-level interactions (reviewed in Burkle and Alarcon 2011; Vazquez et al. 2009). Pollinator network analysis has generally shown that, within sites, there is substantial interannual variation in what pollinators interact with what plants, but despite this variation, pollination events still take place, potentially indicating resilience to environmental change. Interestingly, despite natural variation in who interacts with whom, structural properties of community plant–pollinator networks remain fairly constant over time (reviewed in Burkle and Alarcon 2011). For this reason, it is possible to use network metrics, like **nestedness** and **connectance** to indicate, over and above this natural variation, the health and stability of interactions and potential directional change over time due to anthropogenic environmental changes. Highly nested networks are fairly robust to environmental change (Bascompte et al. 2003); thus declines in the nestedness of a network over time can serve as a barometer, indicating loss of functional resilience in plant–pollinator interactions.

Pollination networks can be utilized to understand community-level impacts of climate change via two main approaches: (1) evaluation of networks after simulated biodiversity loss or phenological mismatch and (2) comparison of networks after actual habitat restoration. We discuss both in the sections below, respectively.

4.11.1.2.4 Simulated Biodiversity Loss or Phenological Mismatch

Simulation studies use existing plant–pollinator networks to simulate the effects of environmental change, for example, they help us to understand what happens when we delete species or advance the phenologies of species, as might be predicted by climate warming. For the most part, these simulation studies have found that pollination networks are more robust to the removal of random species than to the selective removal of highly linked species (Kaiser-Bunbury et al. 2010; Memmott et al. 2004). Many studies have found that the removal of the most-linked pollinator species results in a relatively linear decline of plant species, explained by the nested interaction network topology and a redundancy in pollinator links per plant (e.g., Memmott et al. 2004). In another simulation study, Devoto and colleagues (2007) removed species from the network that they predicted would exhibit spatial range shifts due to climate-change induced increased precipitation, and found that removal of these species had fairly minimal impacts on the plant–pollinator network. In another simulation study by Kaiser-Bunbury et al. (2010), the authors allowed species in the network to switch to those that they have known potential to interact with, with the interesting finding that networks could be stabilized following species loss if remaining species could indeed 'rewire' to form new interactions. While results from these simulation studies suggest that pollinator networks may be more robust to species loss and range shift than other ecological networks (e.g., Dunne et al. 2002), it is important to keep in mind that plants and animals may be differentially impacted by biodiversity loss, given that pollinators represent higher trophic levels, which are inherently more sensitive to habitat disturbance (e.g., Holt et al. 1999; Kruess and Tscharntke 1994). Because pollinators are dependent on plants for food, it is not surprising that removal of the strongest interacting species in the network can have the strongest negative impact on simulated animal extinction rates (e.g., Kaiser-Bunbury et al. 2010).

Just a few pollinator network studies have examined the impact of climate on pollinator networks by modeling plant and pollinator phenology (Memmott et al. 2007, 2010). In these studies, Memmott and colleagues use existing predictions of temperature changes (e.g., IPCC 2001) to calculate potential phenological shifts in plant and pollinator emergence and senescence, if those predictions are accurate. In their 2007 study, Memmott and colleagues examined simulated networks where the onset of flowering and flight activity of all plants and pollinators would be advanced by 1, 2, and 3 weeks. Across all three scenarios, they found that 17–50% of all pollinator species, especially those with smaller and more specialized diet breadths, faced reduced floral resources and potential extinction. Similar to the findings of other network studies, the predicted impacts on pollinators were much greater than for plants, though plants still experienced a 50% reduction in pollination activity, likely leading to reduced reproduction and eventual population decline (Memmott et al. 2007). In a following study, Memmott and colleagues asked specifically how the sowing of wildflowers changes the impact of simulated climate on the pollinator network. Their experimental planting and simulated climate-impacted network showed that by sowing plant species that bloomed at the beginning and end of the flowering season, the overall period of nectar resource availability could be extended for pollinators. However, it should be noted that these simulation studies did not allow for behavioral flexibility, which might allow for new interactions to develop between plants and pollinators within the system.

Another potential interaction between climate and pollination systems may be the introduction of non-native species into the pollination network (Memmott and Waser 2002; reviewed in Schweiger et al. 2010), which may occur if non-native species become invasive under those environmental change conditions (reviewed in Dukes and Mooney 1999; Walther et al. 2009). Depending on whether non-native plants interact negatively or positively with native plants, their invasion could stabilize or destabilize pollinator networks. Examination of a plant and pollinator network in central United States has shown that non-native plants are far more common than non-native pollinators (Memmott and Waser 2002). In this study, non-native plants interacted with significantly fewer pollinator species than native plants, but were still relatively well connected in the network. Likewise, in another simulation study specifically examining the removal of non-native species, the pollination network's structural integrity was diminished by non-native species loss, due to the high levels of connectivity between alien and native species within the pollinator network (Valdovinos et al. 2009). Thus, if non-native plant species increase overall floral resource availability and duration, they may positively impact pollinator populations in the short term. However, the long-term effects of non-native plant species on pollinator populations are not well known. Invasion, which leads to plant species declines and losses in resource heterogeneity, may negatively impact forager biodiversity, as seen in other systems (e.g., Macarthur and Macarthur 1961; Shmida and Wilson 1985; Tylianakis et al. 2008). Overall, these studies suggest that non-native species play varying roles in pollinator networks, depending on their ability to provide foraging resources and their impact on the native plant community.

4.11.1.2.5 Network Comparison Post Habitat-Alteration

Comparing interaction networks before and after an event (habitat destruction or restoration) can tell us more about the maintenance of pollination services than typical biodiversity studies can. Unfortunately, though empirical research on the spatial and temporal variation of plant–pollinator networks is badly needed, the lack of historic data and the intensive sampling effort required to identify multiple empirically gathered networks has limited research in this area (Hegland et al. 2009). Only a few empirical network studies have specifically examined how habitat alteration impacts network architecture. Forup and Memmott (2005) compared pollinator networks for old intact hay meadows and restored hay meadows (planted with native plants post-agriculture), and found no significant difference between the two in terms of plant or insect species richness or abundance, but did find that old meadows had a slightly higher proportion of potential links between plants and pollinators. In a second study, Forup et al. (2008) examined ancient and restored heathlands and found that, while the plant and pollinator communities were similar, the interaction networks were significantly less complex, in terms of connectance values, in the restored heathlands. These results suggest that even in 'restored' human-altered landscapes supporting similar levels of species diversity, the complexity of plant–pollinator interactions may not be easily recreated, and this may ultimately limit the long-term persistence of plant and pollinator communities. In communities with high degrees of network complexity, such as the species-rich plant and pollinator communities of the tropics (Bawa et al. 1985), network recovery post human-alteration may be less likely.

Most remaining studies have examined plant–pollinator interactions over time within the same sites, and these have largely focused on intra- and inter-annual variations in network dynamics (reviewed in Burkle and Alarcon 2011). Studies comparing networks within a single year have often found substantial species turnover in composition, emphasizing the need to consider plant–pollinator networks for shorter and more biologically relevant time periods (Basilio et al. 2006; Jordano et al. 2003; Medan et al. 2006; Petanidou et al. 2008). One study that examined plant and pollinator interactions on a daily basis, also found pronounced species turnover, and found that the most connected species, and thus perhaps the most resilient species, were those with the longest flowering–foraging periods (Olesen et al. 2008). Studies that have examined variation in pollinator networks across multiple years have also found a large degree of turnover in species composition, but have surprisingly found that the number of plant and pollinator species, connectance, degree of nestedness, and modularity were conserved over the years (Alarcon et al. 2008; Burkle and Irwin 2009; reviewed in Burkle and Alarcon 2011; Dupont et al. 2009; Petanidou et al. 2008). Overall, these studies indicate that plant–pollinator systems are dynamic, but that pollinators are flexible in resource use, potentially making networks more resilient to climate change. Furthermore, they indicate that high levels of connectance and nestedness allow for functional redundancies in the network, and greater potential resilience to climate change-induced biodiversity loss. However, research on pollinator networks over multiple years is sorely needed (reviewed in Burkle and Alarcon 2011), specifically research which examines how habitat alteration and environmental change impacts complex and spatially explicit pollinator network architectures (reviewed in Gonzalez et al. 2011). These future studies will greatly improve our understanding of environmental change impacts on pollinator community dynamics.

4.11.2 Ecosystem Service Changes

As mentioned earlier in the chapter, plants and pollinators provide a number of critical ecosystem services. Throughout this chapter, we have discussed research indicating that alterations in local and regional climate can disrupt plant and pollinator phenology, potentially leading to population and community alteration. In our discussion of pollinator networks, we have further shown that simulated alteration of plant and pollinator phenology can lead to marked changes in community-level interactions. The consequences of these population-level and community-level alterations on ecosystem services could be various, and include potential changes in the quantity, quality, spatial availability, and temporal availability of ecosystem services. Unfortunately, research that directly examines the impact of the various dimensions of local climate change on pollination service acquisition is rare to nonexistent. In the following paragraphs, we discuss how potential outcomes of warming or warming and drying scenarios, specifically reduction in the abundance and diversity of pollinators, may impact ecosystem services provided by wild plants and native pollinators.

4.11.2.1 Wild Plant Pollination

The impact of pollination disruption on wild plant communities and the ecosystem services they provide is potentially wide-ranging, but largely understudied (Tylianakis et al. 2008). Though more than 75% of wild plant species are dependent on insect pollination for reproduction (Ollerton et al. 2011), the impacts of this dependency on community or population level ecosystem services are not clear. Most existing studies have focused on single-species analyses of wild plant reproductive success across varying habitat treatments (e.g., Fenster and

Dudash 2001; Jules and Rathcke 1999). A recent meta-analysis of these studies has found that self-incompatible pollinator-dependent plant species exhibited greater declines in fragmented habitats than self-compatible plant species (Aguilar et al. 2006), and cross studies, the effects of fragmentation on pollinators were highly correlated with the effects on plant reproduction. Both of these findings suggest that pollination limitation could be a key driver for wild plant population decline. Of the wild plant species studied, 62–73% show pollination limitation (Ashman et al. 2004; Burd 1994), and though the long-term consequences of pollen limitation on population growth are uncertain (Hegland and Totland 2008), simultaneous declines in native plant and pollinator populations suggest a link between these two patterns (Biesmeijer et al. 2006). Thus, wild plants may face declines if their pollinators exhibit climate-induced spatial or temporal change, or general population decay.

Biodiversity loss in wild plant communities can have devastating effects on ecosystem services because wild plants are critical for ecosystem processes in both natural and human-altered landscapes. Aside from providing humans with food, medicines, fuel, and construction materials, wild plants also support important processes in agricultural, rural, and urban landscapes, such as pest-predation (reviewed in Chaplin-Kramer et al. 2011), nitrogen fixation (e.g., Hooper and Vitousek 1997), erosion control (e.g., Philpott et al. 2008), water filtration and storage (e.g., Lin and Richards 2007), and carbon sequestration (reviewed in Hooper et al. 2005). Lastly, wild plants provide habitat needed for the migration of important seed dispersers and serve as plant propagule reservoirs for the recolonization of disturbed habitats (e.g., Jha and Dick 2008). Thus, wild plants are critical for the function and regenerative capacity of natural and human-altered landscapes, and their decline would undoubtedly reduce the depth and range of ecosystem services they currently provide.

4.11.2.2 Crop Plant Pollination

As discussed in the introduction of the chapter, animal pollination is important for crop production and contributes to the stability of food prices, food security, food diversity, and human nutrition (Steffan-Dewenter et al. 2005). An estimated 15–30% of the American diet depends on insect pollination (reviewed in Losey and Vaughan 2006) and globally, the cultivation of pollinator-dependent crops is growing (Aizen et al. 2008). Thus the loss of pollinators, without strategic market response, could translate into a production deficit of an estimated −40% for fruits and −16% for vegetables (Gallai et al. 2009). These studies all suggest that climate-induced pollinator declines or disruptions to crop pollination could result in the alteration or reduction of food quantity, quality, diversity, availability, and nutritional content, potentially compromising global food security.

4.11.3 Mitigation Possibilities

A number of options exist for improving conditions for pollinators and buffering disruption of pollination interactions and general biodiversity loss. Unfortunately, very little research on pollinator restoration has been conducted specifically in the context of climate. In the following paragraphs, we present mitigation strategies that have been developed with respect to other types of environmental change, as they serve as key starting points for climate-specific restoration strategies. Though many of the practices for pollination restoration are similar, restoration projects can vary in their specific objectives and thus may have different concepts of restoration success (Menz et al. 2011). In particular, we focus on local and regional habitat mitigation strategies that are aimed at increasing the abundance and diversity of native pollinators, but also briefly discuss the challenges and opportunities for better developing pollinator restoration practices in the context of climate. Generally, the best insurance for protecting pollination services in the face of any alteration in local and regional climate involves maintaining or restoring high abundances and diversities of wild pollinators, their food plants, and their nesting resources throughout their current and predicted geographical ranges.

4.11.3.1 Local Habitat Restoration

Research on local habitat restoration strategies is the most well-studied area of pollinator conservation and includes a wide range of on-site practices, such as the sowing flowering strips and installation of hedgerows. Pollinators are dependent on both flowering and nesting resources (Kremen et al. 2007; Potts et al. 2005; Williams et al. 2010; Winfree 2010). Thus, it is essential to consider pollinator nesting and floral resource needs while deciding on the location, size, configuration, and longevity of the restoration. When considering the selection of plants to include in the local restoration, it is also critical to consider nectar and pollen needs of the target pollinator community across their foraging periods (e.g., Dixon 2009; Williams et al. 2010). Some studies suggest the strategic planting of **'framework'** and **'bridging' plants**, which respectively, provide resources necessary for supporting large pollinator numbers and provide resources during resource poor time periods (Dixon 2009). Bridging plants may become even more important, if there is a mid-summer decline in floral resource availability associated with warmer conditions (Aldridge et al. 2011). Furthermore, it is important to consider the facilitative and competitive interactions between the plants within the restoration in order to select a mix that optimizes resource availability for pollinators, as well as, reproductive capacity for the plants themselves (reviewed in Menz et al. 2011).

For the restoration location, field margins are the most commonly utilized areas within agricultural areas (Carvell et al. 2004; Meek et al. 2002; Pywell et al. 2006), because they are usually not planted with crop plants and are often long and linear, easing the process of sowing, planting, and weeding. Within crop fields, field margins and adjacent lands, flowering strips, especially those that include non-legume forbs (e.g., Pywell et al. 2006), are a low cost method to provide pollinators with floral resources. These flowering strips have been shown to increase the abundance and diversity of native bees and butterflies for at least a single season, often more (e.g., Potts et al. 2009; Pywell et al. 2006). Resowing of these strips can provide extended resources and also help reduce the occurrence of weeds (Potts et al. 2009). If a longer term restoration is preferred, hedgerows that include woody perennial plants can potentially provide both nesting and floral resources (Menz et al. 2011).

4.11.3.2 Regional Habitat Restoration

Regional habitat restoration strategies for pollinator conservation include the preservation of unmanaged natural habitat and modifications of existing practices on human-managed lands. A number of studies have shown that the preservation of natural habitat within agricultural areas can lead to higher pollinator abundances, richness, and pollination services for adjacent crops (reviewed in Kremen et al. 2007). Furthermore, the presence of remnant habitats can be critical for the colonization of recently restored habitats (Forup and Memmott 2005; Forup et al. 2008). Human-altered regional habitat can also be used to support pollinator populations, if managed appropriately. Minimizing grazing and cutting of grasslands can increase regional floral resource availability (Duffey et al. 1974; Kruess and scharntke 2002) and insect nest site availability (Morris 2000; Woodcock et al. 2007). Pasture that is infrequently grazed can provide bee populations with important floral and nesting resources (e.g., Morandin et al. 2007), and the reduction of fertilizer application, in conjunction with reduced grazing, has been shown to provide improved habitat for a number of butterfly species (e.g., Erhardt 1985).

Whether natural habitat is preserved or human-managed landscapes are modified for pollinator conservation, it is essential to consider the role of habitat restoration in supporting essential regional pollinator dispersal and migration processes, which may vary depending on pollinator community (reviewed in Menz et al. 2011; Powell and Powell 1987; Ricketts 2001). A number of spatial simulation models of pollinator restoration have shown that the best habitat restoration design for pollinator persistence and pollination service was strongly influenced by the foraging behavior of the target pollinator species (Brosi et al. 2008; Keitt 2009). Thus, restoration should keep in mind the dispersal capacities of target pollinator species (reviewed in Menz et al. 2011). For example, for highly mobile species, the restoration processes can consider creating a 'stepping stone' habitat (e.g., Ottewell et al. 2009), whereas dispersal limited species may need more contiguous linear corridors of high-quality habitat (Tewksbury et al. 2002) to facilitate movement through inhospitable matrices. In fact, within agricultural settings, plant populations connected by corridors (Townsend and Levey 2005; Van Geert et al. 2010) or highly biodiverse matrices (Jha and Dick 2010) have been shown to participate in extensive pollen transfer. Thus, habitat restoration that facilitates pollinator movement has the potential to support improved pollination services across natural and human-altered landscapes, particularly in light of current and plausible future changes in local and regional weather patterns and climate.

4.11.3.3 Pollination Restoration and Climate

The habitat-restoration strategies discussed in this chapter provide only indirect options for buffering global climate change; however, the act of increasing pollinator abundance and species richness in a community, at the least, increases the probability that a community or population can persist in altered conditions. Increased population densities and gene flow levels usually lead to populations with greater adaptive genetic diversity (sensu Conner and Hartl 2004). These genetically diverse populations are more likely to be comprised of individuals genetically more suited to altered habitat conditions. Furthermore, there is substantial research illustrating that many ecosystem processes are a function of biodiversity levels (e.g., Balvanera et al. 2006; Cardinale et al. 2006; Naeem 2009) and that ecosystem process change is often less marked when biodiversity levels are high, due to the potential functional redundancy among species (Montoya and Raffaelli 2010) and response diversity (the differing responses of different species to the same environmental change) (Winfree and Kremen 2009). Thus by maintaining high population-level genetic diversity and community-level species diversity, restorations can provide potential safeguards against future ecosystem alterations from climate and other environmental stressors.

Furthermore, it is possible to take the mitigation strategies discussed above and adapt them to the specific situations predicted in global climate model change scenarios. One potential result based on these scenarios is a temporal or spatial shift in species flowering or foraging, which would be likely given that species exhibit varying responses to climate (Parmesan 2007). As discussed in the previous section, one pollinator network study suggests that one way to make pollinator restoration habitats more resilient to future climate conditions is to extend the flowering season of existing restoration areas (Memmott et al. 2010). While this study provides insight into how potential phenological changes could be incorporated into existing restoration plans, there are a vast number of restoration strategies that require further research in the context of climate change. Specifically, future work is needed to examine the role of nesting resources and flowering species density in altered climate conditions.

4.11.4 Conclusions and Policy and Management Implications

While conservation biologists are often focused on taking measures to adapt existing management strategies to whatever climate plausibly could occur in the future or to create new strategies that are more resilient, the goal to develop policies that minimize all human climate forcing needs to be a high priority.

The next line of defense is to ensure that conservation management strategies, both existing and in planning, are designed with climate effects in mind. Many of the recommended strategies for making protected areas more resilient to climate (Heller and Zavaleta 2009) are also those long recommended as best practices for conservation, such as ensuring connectivity between reserves, encompassing latitudinal and elevational gradients within reserves or reserve networks, creating buffer zones around reserves, and ensuring that land-use practices in the matrix are favorable to biodiversity. Given the enormous existing challenges of implementing conservation action successfully (Knight et al. 2008), the concordance between recommended conservation measures for adapting to climate, including plausible changes in local and regional climatic conditions, and other environmental threats is indeed a welcome relief. This concordance also signals how important it is, in the face of climate risks, to enact a full suite of multi-scale conservation measures on the ground to deal with the multiple, synergistic effects of interacting drivers of local and global extinction (Heller and Zavaleta 2009).

Conservation of pollinator biodiversity falls within this general set of recommendations. Thus, rather than repeating this ground, we focus here on the maintenance and conservation of pollination function, rather than pollinators per se, and recommend five key focal points for policy and management, at local and regional scales.

LOCAL:

- Maintaining pollination function in an area requires maintaining a locally diverse set of pollinator species. Diverse groups of pollinators provide enhanced pollination function, through complementarity and other mechanisms (Hoehn et al. 2008; Klein et al. 2009), and are more likely to withstand multiple, potentially synergistic, threats, through response diversity (Winfree and Kremen 2009). Actions that maintain or restore the diversity of pollinators locally are therefore critically important.
- Maintaining the diversity and abundance of floral resources is a key factor in maintaining the local diversity of pollinators (Potts et al. 2003). Therefore, it is important to enact policies and implement actions that provide floral resources in working lands, including agricultural, urban, pastoral, and plantation landscapes. Such landscapes can support high bee diversity under proper management (e.g., Batary et al. 2011; Cane et al. 2006; Holzschuh et al. 2008; Kremen et al. 2002; Winfree et al. 2007a).
- In restoring plant communities to support pollinators, it is important to ensure that a phenological sequence of plants is established that provide bloom throughout the pollinators' flight season (Menz et al. 2011). For added resilience to climate, specific attention should be paid to enhancing resources at the beginning and end of the flight season (Memmott et al. 2010).

REGIONAL

- Maintenance of the regional species pool is equally important. Extensive research has shown that the landscape scale is an extremely important influence on pollinator abundance and diversity (Garibaldi et al. 2011; Ricketts et al. 2008), and that local scale amelioration of habitat tends to augment pollinator diversity and abundance only in the most simplified landscapes (Batary et al. 2011). Therefore, maintaining sufficient natural habitats at the regional scale is critical for supporting healthy pollinator communities and services (Chaplin-Kramer et al. 2011; Kremen et al. 2002).
- Favorable local scale management practices, such as organic farming practices can have landscape level effects that add to the local effects of such management practices (Gabriel et al. 2010; Holzschuh et al. 2008).

Given the critical role of wild pollinators in maintaining a nutritional human food supply (Eilers et al. 2011; Garibaldi et al. 2011; Klein et al. 2007; McGregor 1976), and the recent and widespread losses of our principal managed pollinator, *Apis mellifera* (Neumann and Carreck 2010), policies and conservation management plans should accord special attention to maintaining the diversity and resilience of pollinator communities, especially in the face of global climate change.

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4.12 Controls on Provisioning Services and Forest Productivity: Responses and Risk under Changing Environmental Conditions

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4.12.1 Introduction

Forests are the largest plant community association on earth (FAO 2010) and provide a wide array of services. They occupy 52% of the earth's land surface (**Figure 1**). They are the largest terrestrial primary producers and sequester the largest amount of atmospheric carbon dioxide (CO_2) on land. In the mountainous parts of the world, forests provide protection against landslides and avalanches. Through their interactions with the atmospheric system, forests regulate environmental conditions, preventing seasonal water shortages or dampening the extent of flooding. They provide a physical barrier that protects soils from erosion and reduces sediment loads in water courses. Forests provide a structure that sustains habitat for countless organisms and, as such, contain a large proportion of global biodiversity (S.o.t.C.o.B. 2010). Forests are also a primary source of fuel in many parts of the world and even provide food. Many of the services provided by forests have high societal value but have little direct monetary value associated with them. Other services have well-established economic values: Forests provide fiber for the global wood products and paper industry. In other parts of the world, forests support a large

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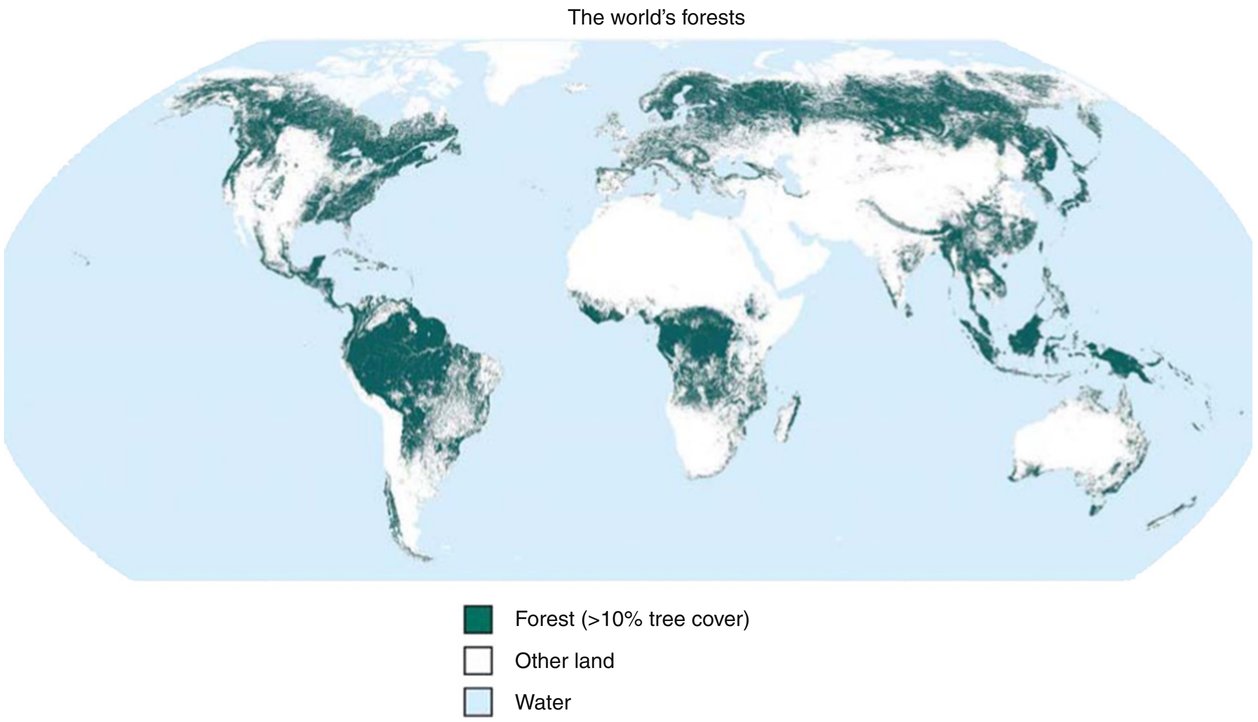


Note: Tree cover derived from MODIS VCF* 250 m pixels for year 2005.

* Moderate-resolution Imaging Spectroradiometer Vegetation Continuous Fields (Hansen *et al.* 2010).

Figure 1 Forested lands of the world as derived from the moderate resolution imaging spectroradiometer (FAO - Global Forest Resources Assessment 2010).

recreational industry. These ecosystem services are essential to sustaining healthy human societies.

The quality and level of ecosystem services are regulated by functional processes that occur in forests. Studies of ecosystem function have greatly contributed to the understanding of sustainable production of forage, fiber, fuel, and provision of water via forests. Without ecosystem functions intact, ecosystem services are greatly reduced. Improved knowledge of ecosystem function and the maintenance of productivity are key factors in determining adaptation measures and mitigation options, as well as in helping to achieve long-term sustainability and stability in the many parts of the world. Even in the anthropogenic progressive buildup of global carbon dioxide (CO_2), the signal of forests is visible. The oscillation in the Keeling curve, a graph that plots the ongoing change in CO_2 concentration since 1958 (Figure 2), is caused by forests. More CO_2 is removed from the atmosphere during the summer in the northern hemisphere, where there is a higher concentration of forests and, consequently, more photosynthesis during the summer months, than in the southern hemisphere summer (Figure 2). This has led many scientists and policy makers to speculate that forest ecosystems can be managed to ameliorate problems related to global warming.

Through ecological services provided by forests, every human is either locally or globally affected by the level of forest productivity in some way. Ecosystem services are often provided in direct proportion to forest productivity. Stability in levels of forest productivity is a good representation of the state of the ecological mechanisms that maintain the structure and services supplied by forests. Forest productivity, driven by these ecological mechanisms, is mediated by conditions at molecular scales, by regional and local environmental conditions, and by disturbance and forest management activity. The strong link between forest productivity and ecosystem services makes forest productivity level a powerful surrogate for the interaction between global environmental changes and ecosystem services.

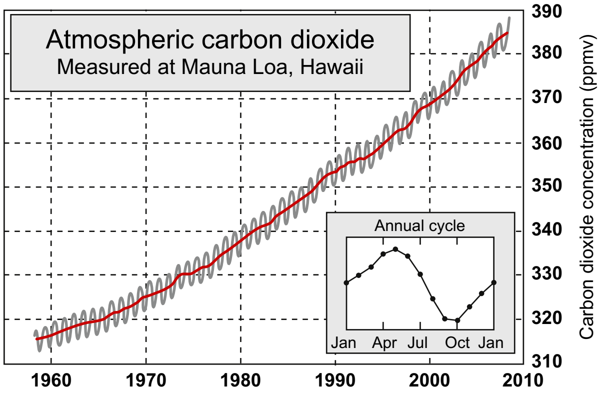


Figure 2 Atmospheric CO_2 levels as measured at the Mauna Loa observatory. This curve is known as the Keeling curve, in honor of Dr Charles David Keeling, the researcher who initiated these measurements.

Forest productivity can be measured in relation to any of the above ecosystem services provided by forests. Forest productivity is most often quantified in terms of carbon fluxes. Productivity begins at the cellular level via photosynthesis, the process by which plants convert carbon into organic compounds. The level of photosynthesis is referred to as gross primary production (GPP) and is a quantity of carbon taken from the atmosphere via photosynthesis. Net primary productivity (NPP) is this amount of photosynthate (carbon) minus the amount consumed by the maintenance of biological processes ($R_{\text{maintenance}}$ – maintenance respiration).

$$\text{NPP} = \text{GPP} - R_{\text{maintenance}}$$

The Intergovernmental Panel on Climate Change (IPCC) (IPCC 2003) defines NPP as the rate of carbon accumulation in plants after losses from plant respiration and other metabolic processes (necessary to maintain the plant's living systems) are taken into account. Net ecosystem productivity (NEP) takes into account heterotrophic respiration such as decomposition of dead organic matter, and thus can be measured from the changes in carbon stocks in vegetation and soil or by integrating fluxes of CO_2 in and out of the system (IPCC 2003; Goulden et al. 1996). Productivity can also be assessed by the level of greenness of forests [e.g., normalized difference vegetation index (NDVI) – (White et al. 2005)], the amount of wood production (e.g., m^3 ha^{-1} (Milner et al. 1996)), or by levels of biomass (e.g., Kindermann et al. 2008).

The environment in which plants are growing is changing. Assessments of how these changes affect forest productivity are crucial to our understanding of how the services provided by forests may also be changing and how adaptation strategies can be developed. In this chapter, we (1) provide a general understanding of the drivers of forest productivity; (2) synthesize documented responses of forest productivity to environmental changes, and based on this state of knowledge; (3) evaluate the risks that come with these and future changes; and (4) present a final synthesis of adaptation and mitigation options.

4.12.1.1 Basic Factors Affecting Forest Productivity

Photosynthesis and respiration are fundamental processes that are the basis for forest productivity and central to ecosystem structure and function. Both respiration and photosynthesis are affected by water availability and temperature, but respiration produces CO_2 while photosynthesis requires CO_2. Photosynthesis is also affected by the amount of incident light. Productivity, as measured by NPP, is the balance between photosynthesis and respiration. Atmospheric CO_2 levels are rarely a limiting factor to productivity. Rather, the basic drivers, temperature, radiation, and water, interact to impose complex and varying limitations on vegetation productivity in different parts of the world (Running et al. 2004; Nemani et al. 2003; Churkina and Running 1998; Boisvenue and Running 2006). Figure 3 depicts the distribution of the limiting abiotic factors to primary production in terms of water, sunlight, and temperature on a global scale. Very few forest types in Figure 3 appear as solid colors, thus expressing variability in the dominance of limiting factors within a given year. For example, the productivity of a forest at northern latitudes is constrained by radiation for some portion of the northern hemisphere winter months due to short day lengths. In late winter, spring or fall, the same forest may have enough light, but low temperature becomes the limiting factor to productivity. Finally, water stress may limit productivity in the warm months of summer. Worldwide, forests have tended to occupy more temperature and radiation-limited environments (Churkina and Running 1998). Currently, less than 7% of forests are in strongly water-limited systems on a global scale.

Temperature (heat) controls the rate of plant metabolism, which in turn determines the amount of photosynthesis and respiration that take place. Most biological metabolic activity takes place within the range of 0–50 °C (Hopkins and Hüner 2004). There is little metabolic plant activity above or below this range. The optimal temperatures for productivity coincide with 15–25 °C, which is the optimal range of photosynthesis

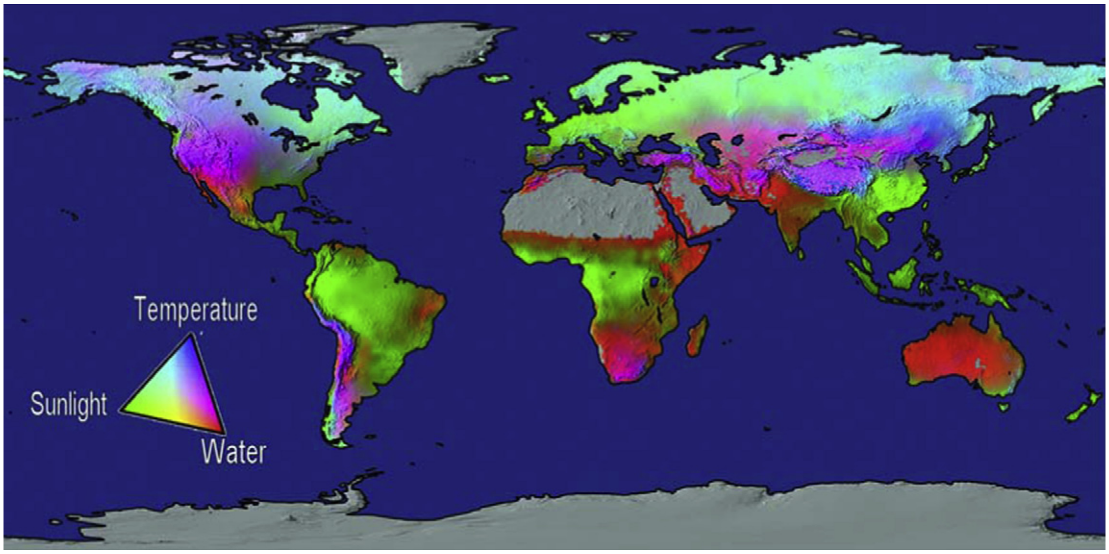


Figure 3 Potential limits to vegetation net primary production based on the fundamental physiological limits of vapor pressure deficit, water balance, and temperature (Boisvenue and Running 2006).

(Hopkins and Hüner 2004). Whereas, temperatures between 44 °C and 52 °C can be lethal (Schulze et al. 2002). Photosynthesis depends on radiation and increases with increasing levels of radiation up to a saturation point. Water is a principal requirement for photosynthesis and is the main chemical component of most plant cells. In dry regions, there is a linear increase in NPP with increased water availability (Loik et al. 2004).

4.12.1.2 Tree and Site Effects

Changes in the basic drivers of forest productivity are first and foremost in determining levels of productivity. If light or water levels are too low or if temperatures are outside the range for metabolic activity, there can be no photosynthesis. Where these basic conditions allow for photosynthesis, the level of forest productivity is further refined by forest type, site, and landscape characteristics. Following the basic drivers, species composition, age and stand structure, site nutrient status, physiological adaptation of the trees, disturbance, and land-use change are the first variables to affect productivity.

4.12.1.2.1 Age and Structure

In addition to stand type and composition, the age and physical stand structure also affect productivity (Battaglia 2001). As forest age increases, productivity generally increases to an asymptote and declines thereafter. However, exceptions to this decline can be found. For example, some old growth forests on the west coast of North America seem to maintain high NPP. High turnover may limit net production of biomass on highly productive sites (Keeling and Phillips 2007). Field measurements demonstrate that biomass, which in many cases is an appropriate surrogate for NPP, rapidly increases in early stand development and tends to stabilize after a certain number of years. The number of years to reach this stability varies by species and forest type, e.g., 200 years in Oregon forests (Van Tuyl et al. 2005). Measurements of carbon storage and fluxes at different developmental stages also show the change in carbon fluxes with increasing age [e.g., ponderosa pine (*Pinus ponderosa* subsp. ponderosa Douglas) forest (Almeida et al. 2004)].

4.12.1.2.2 Nutrients

Nutrients available to support carbon fixation and productivity depend on many intricately related factors. Field data clearly establish a positive relationship between optimum nutritional status, optimum available water, and productivity (Albaugh et al. 2004). The underlying geological formation or geomorphological deposit may contribute to site productivity, but the presence of essential elements does not necessarily make them available for forest growth. For example, nitrogen (N) is one of the most abundant elements on earth. Paradoxically however, N deficiency is one of the most common nutritional problems affecting plants worldwide. N is an important component of many structural, genetic, and metabolic compounds in plant cells and a major component of chlorophyll, the molecule responsible for photosynthesis. Microbial communities, the presence of biological N fixers, external N inputs, turnover dynamics, and levels of other nutrients such as sulfur and phosphorus [see (Braun et al. 2010)] are only some of the interacting factors that determine the level of available nutrients (including N) for forest productivity. Forest soils and site productivity are affected by changes in site water balance and temperatures since they affect soil organic matter decomposition rates (Kirschbaum 2004; Barrett 2002; Moore et al. 1999; Trofymow et al. 2002). Decomposition rates regulate mineralized nutrients available to plants, which affects photosynthetic carbon gain in nutrient-limited systems (Kirschbaum 2004).

4.12.1.2.3 Physiological Interactions

Physiological responses to changes in environmental conditions are highly dependent on the limiting factors of a particular site to forest growth, which, may vary seasonally for the same location. Some studies have found exponential decreases in productivity with decreased water availability (Webb et al. 1983); others confirm strong correlations between precipitation and productivity (Fang et al. 2001; Knapp and Smith 2001). However, the relationship between productivity and precipitation is not always obvious at finer temporal or spatial scales, e.g., the correlation between interannual variability of both precipitation and productivity levels is not always strong (Brando et al. 2010). This is due to the multiple role of water in metabolic plant activity and in ecosystem level processes such as decomposition and mineralization.

Increasing temperature, which has been shown to have a positive effect on productivity (e.g., Toledo et al. 2011), also increases vapor pressure deficit of the air, thereby increasing transpiration rates. This results in adverse effects on drier sites in summer, unless stomata close in response to other changes, such as an increase in CO_2. Increases in night temperatures, if they exceed increases in daytime temperature, can also reduce stomatal conductance (Kirschbaum 2004). Some tree species seem to be able to alter certain traits in response to environmental conditions. One important trait that exhibits some plasticity is water use efficiency (WUE) (Bergh et al. 2003; Gagen et al. 2011). Physiological traits, such as number of stomata, WUE, and foliage light-use efficiency are thought to vary across ecosystem types, and even within a single tree canopy, but how these traits vary across species and time scales is still under debate (Nichol et al. 2002; Guo and Trotter 2004; Lagergren et al. 2005). In a subsequent section, we give an overview of the observed and modeled physiological responses to changing conditions, including changes in traits.

4.12.1.2.4 Disturbance and Land-Use Changes

Land use and land-use change have more direct effects on productivity. Changing forest types, such as planting a new species following a disturbance or forest removal for urbanization both change productivity levels. The United Nations has established a program aimed at minimizing impacts of land-use change on forests (REDD – Reducing Emissions from Deforestation and Forest Degradation, see http://www.un-redd.org/). Disturbances, especially large-scale and intense disturbances, inherently change the productivity of forests (Metsaranta et al. 2010; Bergeron et al. 2010; Pfeifer et al. 2011) because some or all of the photosynthetic material (the carbon fixing material) is removed during disturbances while other material can be left to decompose (which consumes carbon). Most disturbances are either driven by or indirectly linked to climatic conditions (Bergeron et al. 2010; McKenzie et al.

2004; Collins et al. 2006; Dymond et al. 2010). Disturbances have even been shown to delimitate forest type ranges (Bergeron et al. 2004) or be driven by them (McIntire and Fortin 2006). Historical disturbances (i.e., the sequence of disturbances that have effected a specific site) leave a legacy that affects forest dynamics and by interim, productivity (McIntire et al. 2005).

In summary, beyond the basic productivity drivers (temperature, radiation, and water), forest productivity is affected by tree and site characteristics. These include forest composition, age, structure, site nutrient status, and tree physiological response as well as external inputs or larger-scale changes such as atmospheric deposition, land-use change, and past and present disturbances.

4.12.1.3 Larger Scale Effects

There are less direct controls on forest productivity than temperature, light, and water, and than the tree or site-level characteristics. The level of productivity is further refined by forest phenology, biodiversity, forest stand and landscape dynamics, and by feedbacks between changes occurring in forests and the global environment.

4.12.1.3.1 Forest Phenology

Forest phenology refers to the timing of natural events through the seasons. These events include flushing or budburst, flowering, fruiting, and autumn leaf-fall. Phenology is partly driven by amounts of light, water, and temperature, but also by tree genetics. It dictates when it is possible for plants to photosynthesize. Growing season length determines yearly NPP in temperate and boreal forests (Kimball et al. 2004). Data and modeling demonstrate that spring and autumn climate thresholds impact forest productivity and that responses vary by site and species (e.g., Bergh et al. 2003; Desai 2010). Warming that would decrease winter chilling could result in delayed bud burst and adversely affect flowering and seed germination for some species (Chmura et al. 2011), thereby reducing productivity.

4.12.1.3.2 Biodiversity

Biodiversity, as measured by species richness, has also been shown to affect productivity (Paquette and Messier 2011) but it seems to be less of a factor on more stable and productive environments than in the more stressful environments (e.g., temperate versus boreal forests). Mechanisms such as niche complementarity, where the number of species occupying a site can be increased when species have specialized niches, increase biodiversity and consequently increase productivity through stand structure (Paquette and Messier 2011). Species composition can alter the level of productivity as different species under constant environmental conditions display inherently different levels of productivity. Plantations exploit this differentiation between species (e.g., Mallik et al. 2008).

4.12.1.3.3 Forest Dynamics

Ecological succession drives large-scale changes in ecosystem composition over time. The collective response, however, is still the behavior of individuals; individual trees have to produce seed, disperse these seeds, die, etc., for stand dynamics and ecological succession to occur. Thus, all components of individual tree life cycle (tree seed production, seed dispersal, and tree mortality) indirectly determine forest productivity. Seed production and dispersal are the first step in landscape-level forest dynamics, post-disturbance dynamics, and eventually, in species composition. The level of seed production and how these seeds are dispersed are thereby an indirect component of forest productivity (Nathan et al. 2011). In a similar way, tree mortality has direct effects on the dynamics of woody biomass, species composition, stand structure, wood production, and consequently, on forest response to climate.

Even if the individual tree is the unit of change, landscape, regional, continental, and global assessments are still required. Large-scale assessment is an indicator of ecosystem health. The maintenance of a functioning ecosystem is necessary for the maintenance of ecosystem services – trees alone, although they are the unit of change, do not form an ecosystem with societal services but their collectivity does. Cross-scale analyses (such as looking at productivity at the leaf, tree, and system level) quantify the productivity for the system as a whole and contribute to a better understanding of how processes are linked through scale, how these processes can be maintained and they may permit us to see different processes that act at different scales. At the ecosystem scale, losses due to disturbances are relatively infrequent and difficult to quantify. At the biome scale, however, disturbances such as fires and forest harvest can be considered processes because they occur on a regular basis in one area or another of the biome (Georgii and Yoshiki 2002) and, as such, become quantifiable and perhaps even predictable.

4.12.1.3.4 Forest Bioclimatic Feedbacks

Forests are affected by their environment but they also affect their environment. High temperatures can increase transpiration through canopy conductance returning water particles to the atmosphere, which in turn affects the water content of the atmosphere contributing to modifications to atmospheric processes. Other changes, such as an increase in CO_2, can cause stomata to close and by consequence limit transpiration. Changes in physiological traits happen at small scales but their collective change can lead to global-level responses. These feedback loops are influenced by the physiological modification that occurs when climatic conditions change. These cycles are termed physiological feedbacks. One of these feedbacks is based on the notion that providing plants with higher levels of CO_2 will enhance productivity (CO_2 fertilization effect) and contributing to lowering the anthropogenic increase in atmospheric CO_2 by fixing more CO_2 in plant material. CO_2 levels will certainly affect the productivity of some forests, but experimental and modeling studies reveal huge variations in this physiological forcing.

Another feedback comes from a more physical process where the reflectance contribution of forests to the global energy balance can be changed by the level of energy reflected back to the atmosphere. Albedo is the reflective power of a surface. Forests are generally not highly reflective; only between 5 and 15% of incident radiation on forest canopies is reflected back into the atmosphere. A change in forest cover may sufficiently change the radiative forcing of the surface to enhance or counter the increase in atmospheric temperature. The images in **Figure 4** show the change in land surface

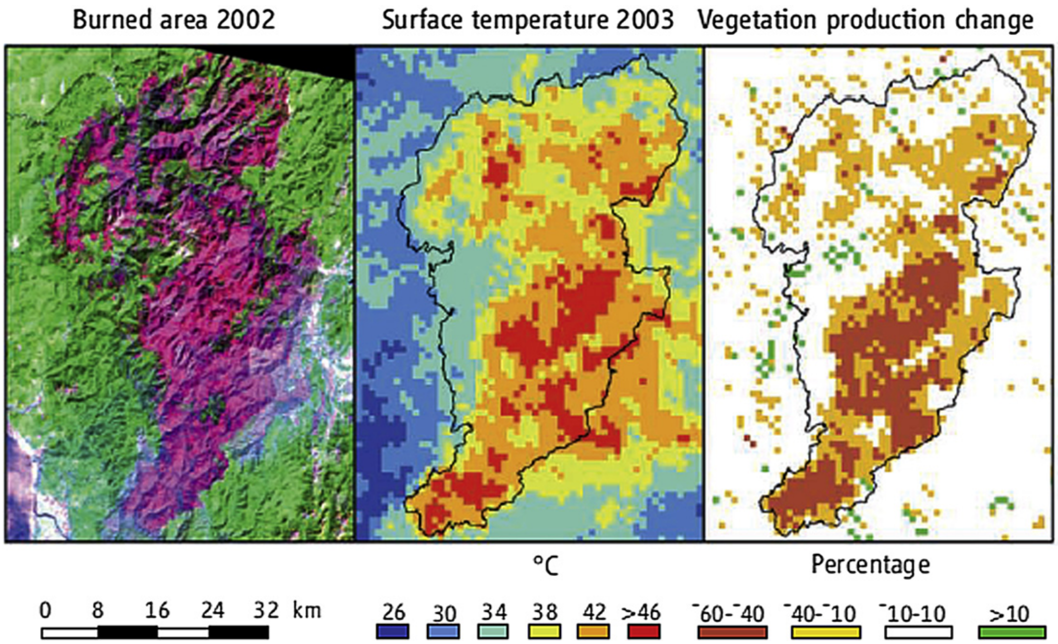


Figure 4 Impact of fire disturbance on land surface energy and carbon balances (Running, 2008). In the summer of 2002, the Biscuit Fire in Oregon burned 2000 km^2 of temperate evergreen forests (left). A moderate resolution imaging spectroradiometer (MODIS) satellite image taken on 28 July 2003 (middle) shows land surface radiometric temperatures of 46–50 °C in the area burned the summer before, whereas temperatures in the adjacent unburned forests range from 27 to 32 °C. Annual vegetation production measured from MODIS (4) (right) was 20–60% lower in the burned area in 2003–04 than before the wildfire.

temperature in the year following a fire in Oregon, on the west coast of the United States. This change in temperature is due to the change in reflective power of the surface and is an important feedback to the atmosphere, changing the energy balance from what it was prior to the fire. Similar changes in reflectance levels may occur if a closed boreal forest becomes more open: There is a process that occurs in the boreal forest called paludification that does exactly this. A more open boreal forest shows much more ground-snow in winter than a closed boreal forest, changing the energy balance of the atmospheric system. There is increasing information available on the effects that forests exert on the global system (e.g., chapter 10B of 64). Unfortunately, most feedback processes are neither well understood nor constrained.

In summary, intricate internal linkages within the forest ecosystem between the forest and the atmosphere bring to light the effects of larger scale processes on forest productivity. Forest phenology, patterns of carbon allocation by individual trees or species to seed production, and the species' mechanism of seed dispersal, as well as its mortality traits, all have indirect effects on productivity levels through forest composition and dynamics. It is also important to assess productivity at different scales of forest ecosystems and to account for the effects that forests have on their local and global environments.

4.12.2 Environmental Changes and Productivity Responses

In many regions, changes in weather patterns and atmospheric composition in the last 50 years have significantly altered the environmental conditions in which forests grow (Jones and Mann 2004). There is evidence that forests have already responded to these changes (Boisvenue and Running 2006; Allen et al. 2010), and changes in environmental conditions are predicted to intensify in the coming decades (IPCC 2007). The IPCC Fourth Assessment Report summarizes many research efforts on climate projections and their potential effects on forests. Forests may have to adapt not only to changes in climate variables, but also to a possible increased variability with, therefore, a greater risk of extreme weather events such as prolonged drought, storms, and floods.

As revealed in the previous section, there is considerable variability in productivity controls across forests systems. For example, changes in rainfall patterns would likely have large corresponding effects on forest productivity in regions where productivity is water-limited. Similar statements can be made about radiation and temperature changes. There is so much variation in space and time in projected environmental conditions and in intrinsic conditions of forest systems, that an example of almost any response can potentially be found. In the following section, we explicitly distinguish between actual responses and projected response. We discuss scale and data issues in the next section (Evaluating Risks) and we consistently attempt to keep the observation scale in perspective when describing responses.

High-latitude regions of North America and Eurasia have been identified as key indicators of the effects of changing environmental conditions because productivity in these regions is limited by the combination of climatically controlled factors, and is affected by compositional atmospheric changes, but is relatively free of other driving forces of productivity changes such as urbanization, political change, and other land-use changes. Much research has also concentrated on these regions and we therefore often default to these forests as examples with empirical data. Process-based models open the way to useful predictions of the future productivity rate of forests and provide a means of assessing the probable effects of variations in climate, disturbance, and physiological forcings on forest productivity. Models are a means of synthesizing known processes or established quantitative relationships that enable the exploration of possible outcomes and enable us to link experimental results with cross-scale monitoring data sources. We therefore include results from modeling research in the following discussions of forest responses to environmental changes.

4.12.2.1 CO_2

The global atmospheric CO_2 concentration is now over 393 ppm, well above preindustrial levels of 278 ppm. There has been much speculation and many experimental and modeling studies that attempt to quantify a generalized effect of increased CO_2 levels on forest productivity. Important research advancements have come from Free Air CO_2 Enrichment sites (FACE). FACE sites use methods and infrastructure to experimentally enrich the atmosphere enveloping portions of a terrestrial ecosystem with controlled amounts of CO_2 without using chambers or walls, effectively removing the constraining 'pot effect' that plagues much of the experimental research. Initial results on the effect of CO_2 enrichment seemed to support an increase in productivity (Nowak et al. 2004; Norby et al. 2005; DeLucia et al. 2005; Körner 2004). The effect of CO_2, however, is currently thought to be site specific (Nowak et al. 2004), constrained by available N and nutrient levels (Beedlow et al. 2004; Lloyd 1999; Norby et al. 2010), with CO_2 levels still contributing to higher productivity on specific sites for specific species (Cole et al. 2010), but likely over a limited time-span. A globally consistent increase in productivity due to a CO_2-fertilization effect is not likely.

Physiological modeling results (Kirschbaum et al. 1998) also show that the effect of increasing CO_2 on forest growth can substantially differ between forests due to interactions with a range of factors that affect nutrient supply.

4.12.2.2 Nitrogen

An important contribution to site nutrient status and hence to productivity, may be the increase in atmospheric N deposition. Atmospheric deposition originating from anthropogenic sources has now become the dominant source of N and varies from ~ 0 to $60\,\mathrm{kg\,ha^{-1}\,year^{-1}}$. Atmospheric N deposition is likely to enhance growth for many forests, where N is considered to be the most common limiting nutrient (Breymeyer et al. 1997; LeBauer and Treseder 2008; Tateno and Chapin Iii 1997). The intrinsic nutrient status of a site will determine the response to additional N deposition (much like that suggested for the response to CO_2). There is a substantial geographic variation in current and projected N deposition levels. At very high deposition levels, N can have toxic effects on plants with 'high levels' being relative to the initial nutrient status of the site. In forests, varying levels of N can change the nutrient balance enough to cause a species shift and increase acidity, especially when N deposition is combined with sulfur (S) deposition that may lead to saturation and elevate base leaching from the soil in some forests, effectively decreasing the nutrient status of the site. High levels of N deposition have been shown to increase sensitivity to stress and disturbances. There are also concerns of the continued effects of N deposition on plant biodiversity: Increases in N inputs may favor specific species and eliminate others. Globally, N and carbon (C) cycles strongly interact and can geographically mediate ecosystem response to N within certain biome types. This strong link means that the impacts of N will have additional repercussions on previously described feedbacks and exchanges between the forest and the atmosphere within the climate system.

4.12.2.3 Other Pollutants

The photochemical oxidant ozone (O_3) and pollutants such as sulfur dioxide (SO_2) have been shown to damage plants (Kita et al. 2000; Potter et al. 2002; Ashmore 2005). However, the combined effects of pollutants, CO_2 levels, temperature, and changes in precipitation are not mechanistically well understood (Kirschbaum 2004; Ashmore 2005; DeLucia et al. 2000, 1994). In localized studies, higher levels of O_3 and other pollutants were associated with insect-related disturbances (Jones et al. 2004), suggesting an increase in pollutant-related stress increases the likelihood of occurrence of other stressors. O_3 was also found to interact with frost (Oksanen et al. 2005), increasing the negative effects of frost on pigment loss and stomatal conductance. Integrating O_3 with CO_2, temperature, and precipitation changes within models, results in varying productivity predictions (Hanson et al. 2005). Single factor studies may help us understand mechanisms but they may not be useful in determining the magnitude of long-term ecosystem responses, since combined factors may cancel or compound each other (we discuss this concept in depth in a subsequent section). There is no doubt that the increase in atmospheric O_3 will modify the response of forest to elevated CO_2, temperature, precipitation, and radiation. But few multifactor experiments currently exist and our modeling efforts are bound by our understanding of the interactions.

4.12.2.4 Growth, Temperature, and Precipitation

Air temperature can have different impacts on photosynthesis and respiration (and consequently on productivity) and responses to temperature vary across sites. Also, how these temperature changes affect forests depends on site conditions at the onset and during each event; increases in growing season length may increase photosynthesis in the spring but also increase respiration at the end of the growing season on the same site. Temperature also has a direct effect on decomposition rates; for example, when water is not limiting, decomposition rates increase (at least initially) with increases in temperature. Increased decomposition rates could result in more readily mineralized nutrients available to plants, which would likely increase photosynthetic carbon gain in nutrient-limited systems. The combined effect of CO_2, N, and temperature increases points to increases in productivity. Indeed, initial reports have shown increases over the latter part of the twentieth century in Europe, North America, and in many forests of the world. Increases in above-ground productivity, a commonly targeted variable in many studies, are not necessarily accompanied by an increase in biomass or below-ground carbon accumulation. Field studies show some forests loosing soil carbon while still exhibiting an increase in photosynthesis and in above-ground biomass accumulation.

Temperature increases can lead to increases in metabolic activity, but there is a threshold beyond which high temperatures with no additional water input lead to drought events. Recently, global reductions in productivity due to drought have been reported with varying responses between the northern and the southern hemispheres, where forests in the northern hemisphere show an increase in the last decade and those in the southern hemisphere showed decreases. To result in a productivity increase, temperature increases must be accompanied by a minimum amount of site water.

4.12.2.5 Physiological Interactions

Physiological responses to climatic stresses are relatively well-understood at the organ or whole-plant scale but not at the stand or landscape scale. The rising atmospheric CO_2 levels during the past century have resulted in increases in WUE for some forests. This, however, has not necessarily prevented growth decline due to warming-induced stress. The modification by trees of their WUE may help with drought-tolerance, but apparently extreme events such as summer droughts do not cause an increase in WUE, at least in the short term. Even though physiological responses are not well understood at coarser spatial scales, natural trait variation can still cause large differences in forest productivity. The magnitudes of these differences may approach those arising as a result of changes to site nutrient status and disturbance frequency. In certain regions of the world, physiological responses dominate: In northern and western Europe, the increasing atmospheric CO_2 level and warmer temperatures are expected to result in positive effects on forest productivity, at least in the short to medium term. In eastern and southern Europe, the negative effects of more frequent drought and increased disturbances are likely to outweigh the positive effect of CO_2 or warmer temperatures. In other systems, like the boreal and even some German forests, productivity is more affected by disturbances as opposed to physiological changes due to environmental changes.

Generally, positive responses of conifers to temperature and CO_2 seem to be reported more frequently, possibly because they benefit from a longer growing season. However, declines in productivity during summer water stress also seem more frequently reported for conifers. Radial growth on the best growing white spruce in Alaska seems to have been disproportional affected by increasing temperature. Drought also increases vulnerability to additional stressors or disturbance and may completely change forest dynamics and hence the structure and productivity, which seems to be the case for the Alaskan white spruce. The key is in the identification of the driving forces for a given site and the initial conditions of that site and its history; for example, is the site vulnerable to drought? Do the species on-site have the capacity for adaptation? Will disturbance dominate? Which ecophysiological or phenological trait responds to environmental changes is strongly correlated with species, other traits, geography, and climate? For a specific species, bud phenology, petiole length, and leaf N may be able to adapt to changing conditions, while the traits related to water use may not change; for another species, WUE may be the most responsive trait. A species' distribution since the last glacial maximum may be a good indicator of a species' ability to adapt with wide-ranging species being more likely to exhibit more plasticity in their traits (Bergh et al. 2003; Chmura et al. 2011; Schumacher and Bugmann 2006; Lindner et al. 2010; Falster et al. 2011; Carnicer et al. 2011; Köhl et al. 2010; Keller et al. 2011; Kang et al. 2006).

4.12.2.6 Structure

The increased productivity in forests of the eastern United States in the last 50 years was at least partially driven by age structure; many forests in this region colonized abandoned fields, resulting in forested landscapes with many young stands, stands that are in the steepest and most productive part of their growth curve. The relative effect of structure versus climate (temperature and water combination), nutrient status, or disturbances on productivity was once again site dependent. In Siberian pine forests, age exerted the most control over productivity, followed by site nutrient status, and effects of damage caused by low-grade reoccurring fires (Van Tuyl et al. 2005; Bergh et al. 2003; Wirth et al. 2002; Kardol et al. 2010; Chapin III McGuire et al. 2010; McGuire et al. 2010; Chertov et al. 2009).

4.12.2.7 Insect and Pathogen Disturbances

Modeling results continue to support an increase in productivity due to the combined effect of CO_2, N, and temperature where water is not limited. However, larger scale processes such as disturbance would result in decreases in productivity swamping any response to CO_2, N, temperature, or any possible management intervention. Insects or pathogen disturbances can greatly alter productivity even if they do not completely kill the forest. Forest conditions are certainly a key variable driving these disturbances: Drought stress can increase the occurrence of insect disturbances and pathogen occurrence, but changes to insect and pathogen populations are also occurring and they will affect forest productivity. Pathogens and insects may benefit from facilitated travel associated with a highly mobile human population and better survival conditions due to changes in temperature and precipitation. Even life-cycle changes in native species, such as the mountain pine beetle in the western part of North America, are having dramatic effects on forests (Figure 5). This small native beetle has effectively killed most pine forests in interior British Columbia, Canada, which is an affected area larger than many European countries (Pfeifer et al. 2011; Dymond et al. 2010; Kurz et al. 2008; Régnière et al. 2010).

4.12.2.8 Fires

Dry conditions are conducive to the occurrence of fires. There are numerous reports that fire frequency has recently increased in the western United States and Canada, across the North American boreal forests, and many parts of Europe. Annual levels of burned area have complex relationships with large-scale climatic patterns such as the Pacific Decadal Oscillation,

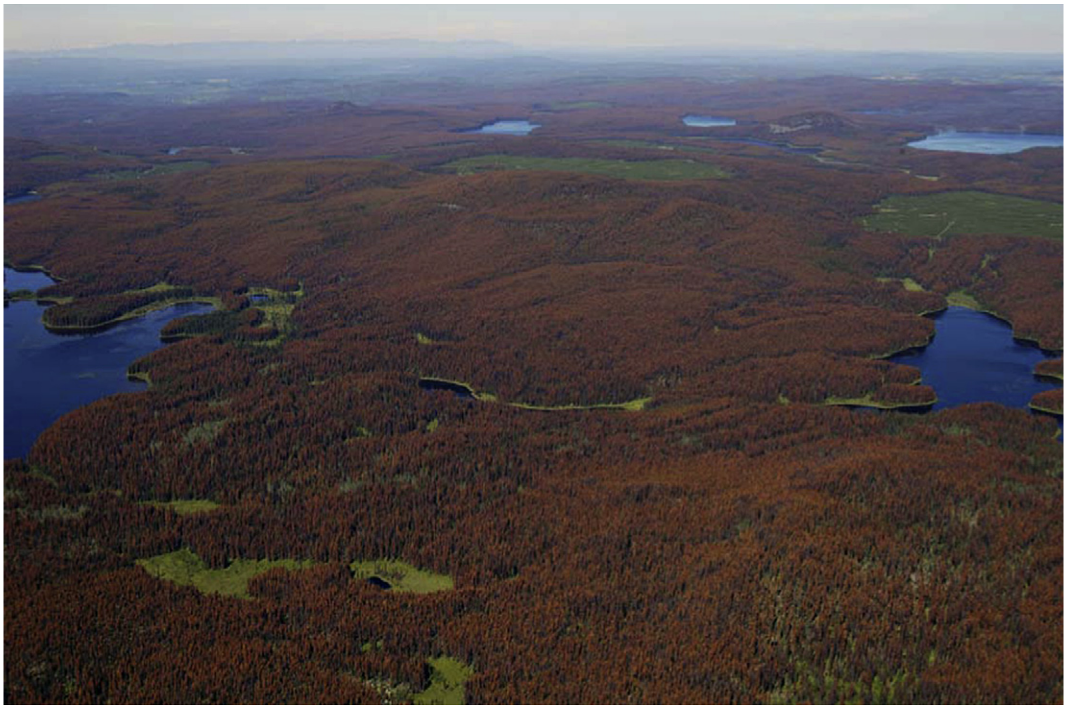


Figure 5 Arial photography of the mountain pine beetle outbreak in central British Columbia, Canada. (Photo credit: Kevin Buxton, Ministry of Forests, BC, Canada.)

the El Nino Southern Oscillation, and the North Atlantic Oscillation. Higher spring and summer temperatures and earlier snowmelt were identified as the main factors extending the wildfire season and increasing the intensity of wildfires in the western United States. These changes are certainly related to larger scale climatic patterns. However, the importance of local and seasonal temperatures and site conditions also suggest that the response of forest fires would be regionally individualistic under the large-scale influence of these weather patterns.

Fire occurrence is also related to other factors such as physiographic factors and human activity. Fire disturbances completely modify site productivity and often drive landscape-level productivity. In forests of the Swiss Alps, fire and physiological responses dominate productivity levels in these forests. Forest fires affect atmospheric conditions by sending a pulse of CO_2 and other gases back into the atmosphere, effectively modifying atmospheric composition. Fires can also drastically change the albedo of the earth's surface, even in the case of less severe fires where clearing of the understory can occur and expose more winter snow for a higher reflectance. Both factors – gaseous pulses and albedo – are feedbacks that can have profound effects on the global energy budget (Metsaranta et al. 2010; Bergeron et al. 2010; McKenzie et al. 2004; Collins et al. 2006; Schumacher and Bugmann 2006; Westerling et al. 2006; van Bellen et al. 2010; Girardin and Mudelsee 2008; Hély et al. 2010; Running 2006; Senici et al. 2010; Macias Fauria and Johnson 2008; Li et al. 2000; Randerson et al. 2006).

4.12.2.9 Mortality

In addition to mortality due to fire, insects, and pathogens, there is currently an increasing number of reports of drought-related mortality events (Allen et al. 2010; Carnicer et al. 2011; Williams et al. 2010; Bigler et al. 2006; Ganey and Vojta 2011; Galiano et al. 2010). Alaskan white spruce is currently experiencing a mortality episode that is thought to be initiated by drought (Soja et al. 2007). There are also reports of large-scale mortality events in Siberian and Canadian boreal forests (Soja et al. 2007), in Scots Pine forests in Switzerland (Bigler et al. 2006), and the Pyrenees (Galiano et al. 2010). Mortality events in forests of the southwestern United States are now well known (Ganey and Vojta 2011). Drought exerts a strong influence on tropical forest metabolism, carbon stocks, and ultimately, the flux of carbon into the atmosphere. Allen et al.'s (Allen et al. 2010) discussion provides a thorough global overview of drought-related whole-stand mortality events. Drought conditions may arise not only from prolonged periods with no or little precipitation, but when precipitation events occur in intense bursts (Lindner et al. 2010; Carnicer et al. 2011; Lines et al. 2010; Williams et al. 2010; van der Molen et al. 2011; Soja et al. 2007; Shiau and Modarres 2009; Misson et al. 2011, 2010; Bigler et al. 2006; Ganey and Vojta 2011; Galiano et al. 2010).

Geographical variation in mortality is substantial and correlated with several environmental factors. Variation in mortality rates is the product of differences in species composition combined with constantly changing mortality–environment correlations within species. The actual response to drought (the extreme response being death) may depend on seasonal timing and perhaps even on the sex of specific trees. Single-season drought events do not necessarily result in mortality, but productivity usually decreases nonetheless. There are fewer reports of decreasing productivity with drought or of partial mortality events, but this may be because detecting small-scale mortality events (e.g., $<30\%$ of a stand) or a decrease in productivity is much more difficult than whole-stand mortality events. Defoliation trends have been reported to be paralleled by significant increases in tree mortality rates in drier areas that are related to tree density and temperature effects. Under the combined effects of drought and defoliators, these forest tree species actually responded by altering their crown leaf structures with increased percentages of defoliation in the drier parts of their distributions.

4.12.2.10 Species Shifts

Fire regimes have been identified as the dominant process in defining boundaries of certain forest types (e.g., boreal mixedwoods and coniferous forests). In some regions, landscape composition perfectly follows the boundaries of past fire events. Biogeographical modeling suggests that species distribution would shift along with changing environmental conditions. Increasing levels of mortality due to drought, fires, insects, and pathogens would certainly contribute to this shift. Biome shifts are reported in Alaska (Soja et al. 2007; Beck et al. 2011), where the boreal forest seems to be expanding into the tundra, and drought-induced productivity declines in interior white spruce stands are shifting the species composition toward a broad-leaved forest (Soja et al. 2007). Shifts are also reported in the boreal forests of Siberia and western Canada (Soja et al. 2007). No northward movement is apparent in the Canadian eastern boreal forest (Payette et al. 2008), which is much wetter than its western counterpart. Drought-induced dieback of Scots pine in the Pyrenees is being accompanied by oak regeneration (Galiano et al. 2010), indicting a species shift; the temperate-boreal ecotone in Canada has reportedly been moving northward (Leithead et al. 2010); there are reports from the Central Alps of a shift toward more drought-tolerant species (Moser et al. 2010). There are also reported shifts in tropical forests, with modeling research suggesting some regions of humid tropical forest contraction, but also some areas of expansion (Zelazowski et al. 2011). Species competition in response to drought is strongly related to the survival strategies of each species (Lines et al. 2010; van der Molen et al. 2011; Zelazowski et al. 2011).

Reported and modeled responses of forest productivity changes along with changing environmental conditions seem to agree that increased levels of ambient CO_2 can increase productivity, albeit over the short term and only for specific sites and species. N is identified as an essential component to this CO_2 response. However, similar to temperature (high temperatures leading to droughts), high N levels can become detrimental to productivity levels. Drought events lower productivity and increase the probability of other stressors or disturbances on forested sites. Reports generally agree that the single or combined effect of drought and other stressors could create more mortality events than in the past. To date, some forests show a predominately physiological response to environmental changes, while the response of other forests is dominated by disturbances. In the next section, we attempt to use acquired observations and knowledge to evaluate the risks to forest productivity that are brought on by environmental change.

4.12.3 Evaluating Risks to Forest Productivity

4.12.3.1 Uncertainty

Before evaluating the risks to forest productivity from current and projected environmental changes, it is important to assess the information that is currently available and on which an evaluation should be based. We start this section by providing a critical assessment of the data and mechanisms that the responses section is based on. We then identify known knowledge gaps that affect the accuracy of interpreting responses, diagnose the limitations of our current synthesis abilities, and look at the potentially compounding effects of the multiple factors affecting productivity. Based on the state of knowledge, we provide an overview of the identifiable risks that environmental changes pose to forest productivity.

4.12.3.1.1 Data, Experiments, and Models

The present understanding of the mechanisms that result in forest productivity come from three main sources: observational data, experimental data, and modeled responses. None of these information sources is perfect. Observational data are limited by sample size, length of observation (time), and spatial scale. Experimental data, resulting from a manipulation of affecting factors, are limited by the number of factors that is possible to change while maintaining an acceptable level of statistical power. Models are often limited by our computational capability and when they are not, they are limited by the extent of the knowledge that can be integrated into model design. All are limited by our ability to analyze, interpret, and understand the system and by research funding.

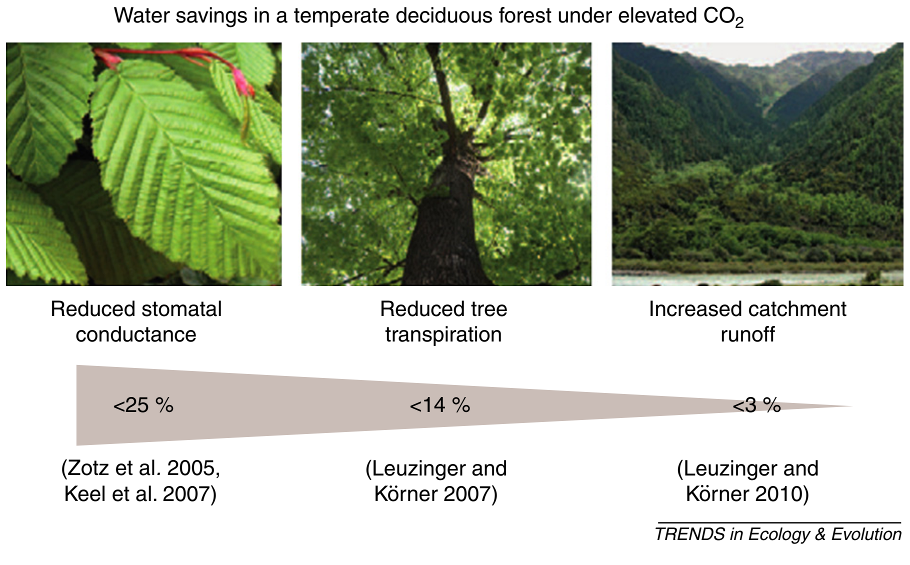
Productivity estimates can come from a variety of data sources. There is often contention on data interpretation with claims of over- or underprediction due to the type or the scale of data used in the analysis, or the analysis itself. Forestry-based data have been claimed to overestimate productivity in temperate and boreal forests (Lloyd 1999), but deciphering the effect of data source among the effects of CO_2, N, temperature, water availability, structure, disturbance, or disturbance history is difficult even with advanced analysis methods. For forest productivity estimates, flux-tower data may be the closest measurement to the actual productivity that is currently available. Flux towers measure the exchanges (mostly of CO_2 and water, but of other gases as well) between the atmosphere and the biosphere. A network of these towers has been established in forest systems around the world. The wealth of information that has come from these sites has contributed to measurable advancement in the understanding of productivity and the links between forest productivity, the atmosphere, and global cycles.

Forest biomass is often equated to productivity. This seems logical given that leaves contain the photosynthetic apparatus and are also an important component of above-ground biomass. However, while this relationship between biomass and productivity is valid for certain sites, it also varies. Processes such as high turnover rates may limit biomass production on highly productive sites (Keeling and Phillips 2007). Some field measurements have revealed biomass to be poorly related to carbon flux and to partitioning of photosynthetically derived carbon (Litton et al. 2007). Field measurements of turnover times also suggest that root production and turnover in forests may have much more site-dependent variability than current generalized estimates suggest (Matamala et al. 2003). These few observations remind us that despite an increasing understanding of carbon allocation in forests, careful attention needs to be paid to how productivity is estimated or inferred, and that the conditions and site for which these estimates were made must be considered before conclusions can be drawn.

Experimental manipulations, both in labs and in the field, are extremely important in understanding the processes that lead to forest productivity. Most of the mechanistic understanding of productivity such as photosynthesis and conductance comes from experiments. However, experiments have their limitations. When attempting to decipher the effect of global change drivers, very few experiments test more than two factors (e.g., elevated CO_2 and increase in temperature). Most experiments test one global change factor. Single-factor experiments do not, however, provide us with the information needed to deduce the magnitude of long-term ecosystem responses. A few experiments have tested three factors (e.g., varying levels of CO_2, temperature, and O_3). In those, the three single effects are analyzed, the three two-way interactions are analyzed, but only one three-way interaction is analyzed. This is mainly due to the complexity of setting up and analyzing such experiments, and the statistical power of such experiments may be poor (Leuzinger et al. 2011). When multifactor experiments are established, they help in deciphering ecosystem response, but they lose much of their ability to make inferences about underlying and interacting mechanisms (Leuzinger et al. 2011). Experiments are also restricted in time. Very few large-scale change experiments have been maintained over 10 years (only two FACE sites), despite the knowledge that the effects of drivers, like the effects of elevated CO_2, may diminish over time (Hättenschwiler et al. 1997) and that forest longevity extends far beyond 10 years.

Experiments are spatially restricted. Laboratory findings may, for example, help understand processes but they do not reflect the reality of actual forest responses. In reality, when longer time periods and larger spatial scales are considered, this inevitably implies a growing number of processes acting on the system. For example, if the carbon or water cycle is studied at the leaf level, many processes are missed that are taking place in other parts of the plant such as symbiotic mycorrhizae or interactions with competing plants and animals. Therefore, if the aim of an experiment is prediction of a net ecosystem response, the experiment should be conducted in as near-natural conditions as possible (Leuzinger et al. 2011). There seems to be a dampening effect when small-scale or single-factor experimental responses are applied at larger scales. **Figure 6**, taken from Leuzinger et al. (2011), shows the example of the measured response to elevated CO_2 at the leaf level and at the whole-plant level. The WUE response to elevated CO_2 at the leaf level is much larger (<25%) than if the same response is evaluated at the tree transpiration level (<14%), and again, at yet coarser scales, the change in WUE measured as runoff is much smaller (<3%) at the catchment level (Körner et al. 2005; Saxe et al. 2001; Ellsworth et al. 2004).

Figure 6 clearly illustrates a scaling issue. There are many more processes influencing measurements at coarser scales, and some processes may even cancel each other out, making interpretation of the results difficult, particularly if all the processes are not identified or their responses are not understood. For example, the increase in WUE of 25% in **Figure 6** scenario did not result in a 25% increase in WUE for the whole tree. This may be due to other processes being adversely


Water savings in a temperate deciduous forest under elevated CO_2

Reduced stomatal conductance
Reduced tree transpiration
Increased catchment runoff
<25 %
<14 %
<3 %
(Zotz et al. 2005, Keel et al. 2007)
(Leuzinger and Körner 2007)
(Leuzinger and Körner 2010)

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Figure 6 Case study at the Swiss Canopy Crane forest FACE site: 11 temperate broad-leaved trees were subjected to 550 ppm CO_2 during 8 years near Basel, Switzerland Leuzinger S., Y. Luo, C. Beier, W. Dieleman, S. Vicca, and C. Körner 2011: *Do global change experiments overestimate impacts on terrestrial ecosystems?* Trends in ecology & evolution **26** (5), 236–241. Shown are results from studies on water use of CO_2-treated and control trees (proportional change in treated compared to control). At equal microclimatic conditions, the percentage reduced stomatal conductance corresponds approximately to the percentage reduced transpiration. The larger the spatial perspective of estimating water use under elevated CO_2, the smaller the response compared to the control scenario. One explanation for the observed phenomenon is the increasing number of relevant processes acting at larger scales (e.g., soil and atmosphere feedbacks, plant–animal interactions, and competition).

influenced by elevated CO_2 (as opposed to positively for WUE) and requiring just as much or more water in absolute terms than in an environment without the CO_2 increase. As the scale gets coarser, the number of processes that are interacting with water use increases. The same is true for the production of photosynthate.

Scaling issues are also important to understand when dealing with different sources of data. In some cases, it is necessary to step back to see the pattern (e.g., with satellites), such as when the signal of large-scale climate patterns such as the Pacific Decadal Oscillation is sought. Conversely, a finer scale may be more appropriate when temperature seasonality effects are sought.

Models have been able to provide some of the information needed to evaluate the responses of ecosystems to changing environmental conditions. They are much less limited by data than experiments, and because of this are not bound by the same inference problem. Models, however, are limited by the information and structure that we impose on them when they are created. They are, by definition, a simplification of an ecosystem. Ecosystem-process models usually incorporate the processes that we know, and quantitative models rely more on response observations (Cramer et al. 2001; Luo and Weng 2011). Similarly, climate models that operate at global scales are a simplification of global circulation, perhaps omitting components that may prove to be essential.

4.12.3.1.2 Knowledge Gaps

It is common practice to extrapolate results from environmental change experiments through either space or time or both in an attempt to integrate all the available knowledge into models and large-scale estimates. Our present limitations in the scaling of processes or their responses affects our ability to estimate forest productivity even for the processes that we mechanistically understand well like photosynthesis – Farquhar described the physical process of photosynthesis at the molecular level in the 1980s (Farquhar et al. 1980). There are, however, processes that are much less understood and also those that affect our productivity estimates, e.g., portions of tree respiration remain unclear. The observations of tree mortality quantitatively linked to drought events are accumulating, but the processes that cause drought-induced tree mortality are still debated (McDowell 2011; Sala et al. 2010; Hartmann 2011) as neither catastrophic cavitation nor carbon starvation is presently well supported. This later process has a direct effect on productivity especially when we are trying to assess the effects of changing conditions, which include an increased probability of drought in many locations. Other unknowns include the effects of changing environmental variables on within-population genetic variability. Genetic variation has been shown to be uninfluenced by climate for some species (Hoban et al. 2010), while in other species, 50% of the variation was explained by climate variables (Normand et al. 2011). New hypotheses for processes acting on forest productivity are regularly being put forth and some may, with additional research and observational support, need to be integrated into our estimates of productivity; for example, a recent article identified 'supertrees' as merge individuals with higher productivity, a process that was observed in harsh environments (McIntire and Fajardo 2011). Physiological mechanisms are not alone in affecting productivity. Economic impacts can also be important and there are still few studies that can be regarded as fully integrating ecological and economic impacts. This is mostly due to our limited knowledge of the global implications of social and economic adaptation to the effects of climate on forests. These missing pieces of information should not prevent the integration of all known processes, but need to be identified so that their impacts (although not quantified) can at least be minimized or recognized when assessments are performed.

4.12.3.1.3 Compounding and Feedbacks Effects

Long-term ecological responses to environmental conditions are strongly regulated by slow processes such as changes in species composition, carbon dynamics in soil, and long-lived plants as well as the accumulation of nutrient capital. Changing conditions may or may not change the speed at which these slow processes occur, but many compounding and/or feedback effects have the potential to drastically change the forest landscape and, consequently, forest productivity. The dampening effect of upscaling small-scale experiments (as in Figure 6) means that both beneficial (e.g., a stimulation of plant growth under rising CO_2 or warming) and negative (e.g., reduced plant growth in response to drought or cooling) effects might be more or less dramatic than expected at larger scales and dependent on what changes concurrently take place. Genetic adaptation and traits variation may dampen the signal of large-scale responses be it through space or time. If the experiment portrayed in Figure 6 were to be maintained over a long time period and over a larger area, all leaves in a landscape could potentially adapt to having fewer stomata (and therefore increased WUE). In turn, transpiration for the whole region would be reduced and that, in turn, would further affect the environment by again affecting the leaves. Even the effect of large-scale disturbance will eventually be dampened through time since trees most probably will recolonize the post-disturbance site. Potential negative consequences of feedbacks come from large-scale ecosystem disturbances such as fires (Mildrexler et al. 2009). Large fires have major impacts on the global carbon cycle because large pulses of CO_2 and other trace gases from terrestrial biomass loss are emitted to the atmosphere during these events. An increased frequency of fires could positively feedback to radiative warming by releasing carbon into the atmosphere, but would also negatively feedback by increasing the surface albedo (Goetz et al. 2007). The rate of burn may not exceed historical bounds for certain regions but the compounded effects of increased fire incidence and forest management combined with increases in burn rate may result in large impacts on forest productivity. The loss of productivity in the white spruce stands of interior Alaska appears to result from the same type of compounding effect. The drought-induced decreases in growth in white spruce in Alaska have occurred in concordance with an increase in disease and insects occurrence, a warming and thawing of permafrost, and an increase in wildfire with postfire recruitment of deciduous species (white spruce seedlings seem to be more vulnerable to dry conditions), possibly fundamentally changing this forest type. Finally, even if a positive response of a given species is sustained over time (e.g., temperature-induced increase in productivity), shifts in species composition have the power to reverse initial trends.

Identifying potential sources of error in estimates of productivity is important since these estimates are the basis for our assessment of the potential effects of changing climatic conditions. To date, we have mentioned the scaling issues of known processes, unknown processes, and potential compounding and feedback effects. In addition to these factors, we must remember that often models need to be simple to be useful. This leads to the exclusion of known factors affecting productivity in many models, such as not integrating the effects of development change or history in current large-scale estimates of productivity (Albani et al. 2006) or not including functional traits together with their effects on the patch and size structure of vegetation in dynamic vegetation models (Falster et al. 2011). Based on global climate model simulations, we often attempt to incorporate drought events, but the length of drought, which has an important effect on productivity, is usually not skillfully modeled (Grant et al. 2006) and neither is fire intensity. Multimodel predicted scenarios of the twenty-first century fire severity are scarce and also have no demonstrated skill even in a hindcast mode, and the stand-typical response to severe fire weather is rarely taken into account.

4.12.3.1.4 Changing Relationships

Much of our understanding of forest productivity comes from existing forests and past experiences. Tree-ring data are the foundation of dendroclimatology studies where past climate data are reconstructed from tree-ring widths. But, relationships that may have been stable in the past are not necessarily maintained in a changing environment. Some speculate that we may be presently seeing such a transition within some northern forests, where divergence between dendroclimatology techniques of estimating past climate and measured temperatures is occurring. Repeated studies are now showing that the long-lasting consistencies between temperatures reconstructed from tree-width data are not consistent with temperatures recently measured by thermometers in northern forests (Briffa et al. 1998; D′Arrigo et al. 2008). Possible explanations for changes in this long-standing relationship include a factor that was not important in the past for forest productivity (or ring development) may now have become relevant, or perhaps a yet unknown physiological response to stresses or other factors.

Errors also stem from the input data: The global climate projections, even when statistically or dynamically downscaled to regions and local areas, when run in a hindcast mode for the past several decades, have shown no skill at predicting climate statistics on these spatial scales without tuning the model results using real-world observations at the spatial scale required for ecosystem function (e.g., see Stephens et al., 2010; Kundzewicz, Z. W., and E.Z. Stakhiv 2010). Skillfully predicting changes in these climate statistics is an even more daunting challenge. Yet, there are claims that we may already be in the higher portion of projected climate (Betts et al. 2011; Rahmstorf et al. 2007). If such conditions would occur, however, stands that in the past were thought to be resilient to change may no longer be. Conversely, other stable states may emerge (Johnstone et al. 2010).

Much of the uncertainty surrounding future productivity levels lie in the uncertainty of projected disturbances. There is high variability in most models' ability to estimate current distributions or conditions. Similarly, there is an inherently large uncertainty involved in making projections into the future. Interpolated long-term weather observations from local weather stations and gridded data products, which are the inputs for forest productivity models, yield biased projections (Cook & et al. 2010) since they are smoothed surfaces. Climate modeling has been the basis for modeling effects on ecosystems, but climate modeling has its own inherent uncertainties. For best results, these uncertainties must be quantified and propagated into simulations (Sushama et al. 2010). However, these model projections, at best, only provide a subset of what is possible in the future (Pielke and Wilby, 2012).

4.12.3.2 Risks

Despite these caveats and uncertainties, there is published evidence that allows us to identify some of the potential risks for forest productivity in future changing conditions. In forests with temperature-limited constraints on productivity, which includes high-latitude forests and high-altitude forests that are not constrained by water or that will receive additional precipitation along with the increase in temperature, productivity will increase with temperature. Changes in past productivity are thought to have been dominated by changes in N deposition. Conversely, changes in temperature and precipitation may be the major driver for future productivity. N deposition may still have a positive affect in N-depleted systems, but limitations in base cations, especially magnesium and phosphorus, may significantly affect predicted productivity in the future (de Vries and Posch 2010). Areas of high N deposition such as parts of Asia, the northeastern United States, and some parts of central Europe are at risk of productivity decreases due to changes in site nutrient status caused by high levels of N.

In a warmer environment, forests might become increasingly vulnerable to higher background tree mortality rates and die-off in response to heat waves and drought, even in environments that are not normally considered water-limited. Increases in the frequency, duration, and/or severity of drought and heat stress associated with climate could fundamentally alter the composition, structure, and biogeography of forests in many regions. All areas at present risk of drought could be at greater risk and neighboring areas might become water-limited.

Tree species may respond to drought by modifying certain traits such as WUE, which collectively may help dampened impacts of drought in specific regions. In the long-term, however, direct climate effects on forest physiological adaptation response or on forest dynamics may be small relative to autogenic successional processes or climate-related insect outbreaks (Kardol et al. 2010). Recent changes in temperature and precipitation have already resulted in changes in insect dynamics (Moraal and Jagers 2011; Raffa et al., 2008) and in forest pathogen dynamics (Sturrock et al. 2011). If temperature and precipitation change further, the effects of both forest diseases and insects will become more prominent and may result in changes in forest dynamics.

With increasing temperature and more variable precipitation, increases in fire frequency could contribute to increasing the level of atmospheric CO_2 and other atmospheric gases, representing a positive biogeochemical feedback, but also potentially a negative radiative feedback with a change in surface albedo. Figure 7 shows an example of a potential shift in forest biomes and a potential change in wildfire frequency away from a 1961–90 baseline, based on a selection of climate projections.

Further, the influence of soil conditions on tree migration is not well understood. A particular example of the impact of tree fecundity and dispersal adaptation has occurred in central Chilean Patagonia. Approximately 50–60 years ago, part of the temperate broad-leaved forest was burned to clear land. Much of the 2.8 million hectares of burned forest still remains as grassland today, mostly because of inherently low diversity with the two dominant tree species are not adapted to fire disturbance, nor are they adapted to wind dispersal. This example is not related to climate-induced changes, but illustrates well the potential impacts of a new disturbance when species are not adapted to that particular disturbance. In the Chilean Patagonia example, one cohort of native species has reestablished on the perimeter of the remnant old forest, but at now 50+ years of age, these trees are still not producing seeds. In a parallel effort to maintain soil stability on the mountainous region, forest managers have planted three North American pine species. To date, we know of no data indicating a successful recolonization of the burned area with exotic pine species. However, such occurrences may become reality in the future, as changing environments where fires and large-scale disturbances dominate forest changes, in places not adapted to fire. At broad scales, tree species migration would almost certainly occur with changing environmental conditions and increased disturbances. However, local and regional soil and site properties combined with species fecundity response to changing conditions, and the specific species' ability to disperse seeds, may dictate their migratory response.

4.12.4 Adaptation/Mitigation Options

Determining the possible adaptations of a particular site or region requires the amalgamation of known information across scales and recognition of the unknowns and their associated uncertainties. Probability of abiotic changes (temperature, precipitation, CO_2) can be generally deduced from existing information from the historical record, recent paleorecord, extreme events, and climate model scenarios for almost any forested site. Vulnerabilities of services provided by forest can be identified by combining what is known of these larger scale forcings with the specific conditions of the site or region. The capability of forest ecosystems to adapt depends on forest characteristics, the extent of the environmental changes, and

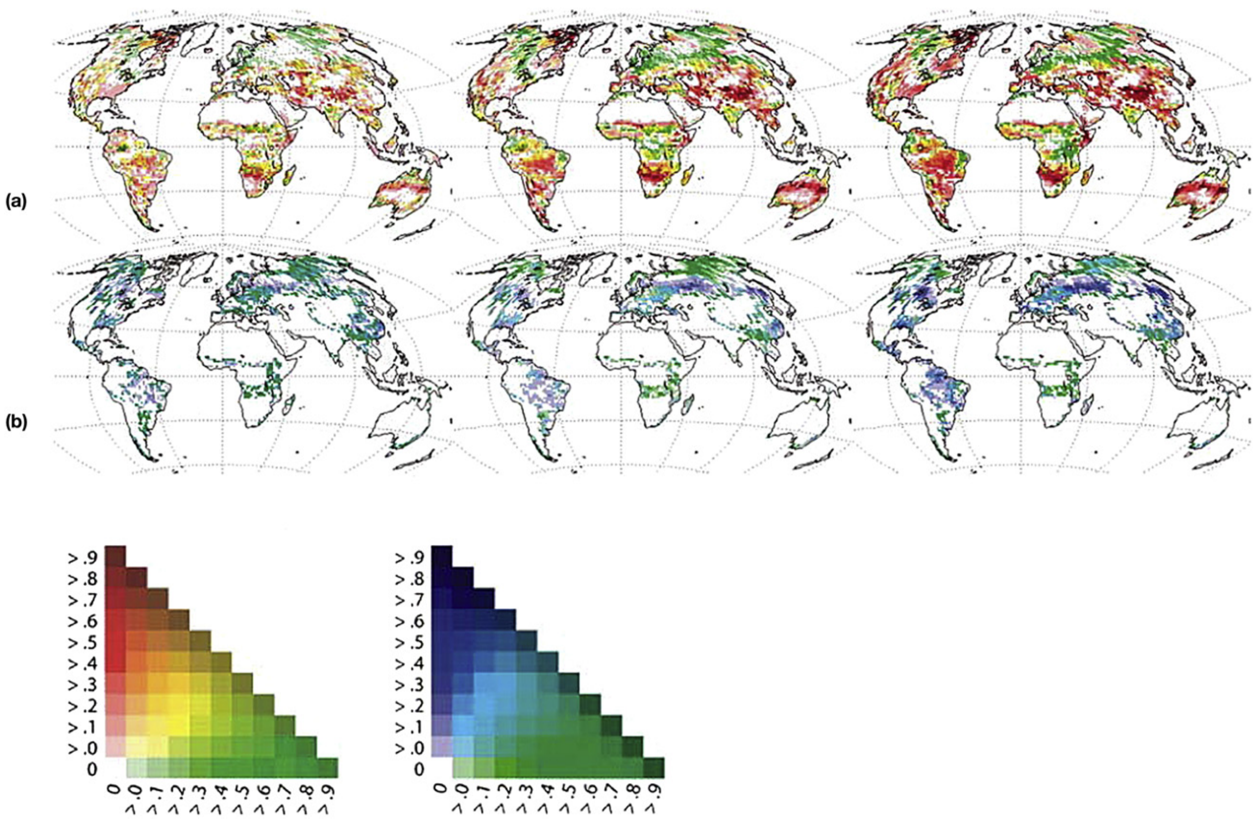

Figure 7 Results from modeling projections based on global circulation model projections Scholze M., W. Knorr, N. W. Arnell, 2006: *Prentice IC: A climate-change risk analysis for world ecosystems*. PNAS **103** (35), 13116–13120. Probability of exceeding critical levels of change between 1961–90 and 2071–2100 for wildfire frequency (a) and of a change in biome from forest to nonforest (b). For wildfire frequency, critical change is defined where the change in the mean of 2071–2100 exceeds $\pm 1\sigma$ of the observed (1961–90) interannual variability. (a) Wildfire frequency (red, increase; green, decrease). (b) Biome change from forest to nonforest (blue) or vice versa (green). For wildfire frequency and biome change, colors are shown only for grid cells with <75% cultivated and managed areas.

the socioeconomic factors determining the capability to implement planned adaptation. A variety of psychological, social, and institutional barriers to adaptation are exacerbated by uncertainty and long timeframes, with the danger of immobilizing decisionmakers. Complexity and uncertainty can be reduced by a systematic approach to categorizing the interactions between decision lifetime, the type of uncertainty in the relevant drivers of change, and the nature of adaptation response options (Warren 2011).

The following section provides basic knowledge about how forest might adapt to changing environmental conditions. A general framework is presented that permits the integration of the larger scale and local factors delimiting the range of possible adaptations for a specific site. This framework is one management avenue for the uncertainty inherent to changing conditions. Finally, this chapter ends by providing examples of possible mitigation actions and identifying some specific research areas that would reduce the uncertainties associated with selecting mitigation options.

4.12.4.1 Possible Adaptations

Adaptation to changes may happen in many ways. Individual species might adapt through phenological and/or genetic changes and/or might shift their distribution. Adaptation may also occur through a modification of trees, plants, and organisms associations. Different species mixes may emerge with the new environmental conditions. Some adaptations may reduce productivity and ecosystem services that forests presently provide, others may increase productivity, and some may maintain their present level. There are very few ecological processes that are driven by one factor. Forest growth and productivity represents a combined record of species genetic and environmental forcings, one of which is climate. Phenological adaptations occur when the climate-related stressor is within the response envelope of the species such that individuals can adjust behavior, morphology, or physiology to accommodate the change. For example, some species have already adapted with early spring flowering to match the earlier spring onset, and as in the elevated CO_2 experiment (**Figure 6**), some are able to vary their stomata number in elevated CO_2 conditions. These adaptations do not involve genetic changes. Changes in gene frequencies are caused by natural selection and may emerge as an adaptive evolution. This type of adaptation is more common in fast growing organisms or organisms that have short life cycles. Forest insects may already be showing some genetic adaptation to changing conditions. Forest trees are long-lived organisms and the effects of changing environmental variables on within-population genetic variability are not yet known. There is no evidence of genetic adaptations in forest trees to the environmental changes presently occurring.

Species may shift their present distribution in response to changing environmental conditions. Range shifts have already been reported. More drought-tolerant species seem to be shifting to regions with increasing drought conditions, like in the Mediterranean region. The northern tree-limit is reported to have already moved north in boreal Alaska and western Canada, and temperature-limited altitudinal tree lines have also been observed to climb. Species movements would be likely with an increasing intensity of environmental changes. This could lead to new combinations of species with new forest dynamics behavior. Invasive species are also more common, could be part of the new combinations, and could even be part of new stable states in forest dynamics. Phenological adaptations, genetic changes, and species shifts may all be concomitantly occurring. Monitoring and reporting changes in species distribution and combination and in phenological adaptations will be the key to seeing which of these is or is not occurring and the extent of each adaptation.

4.12.4.2 Decision Framework

Productivity–climate relationships often vary at relatively small spatial scales (Nakawatase and Peterson 2006). Each location has a set of conditions (local and global) that has resulted in the present state of forest productivity. Local conditions are paramount in determining how changes may affect forests, but local relationships may also be overpowered by large-scale events. **Figure 8** presents a framework that combines both local and global conditions to delimitate the possible adaptation outcomes. From these possible adaptation paths, the effect of changing conditions on forest productivity can be evaluated and management options identified.

Each location can have its own set of probable outcomes. In a location where the past drivers of productivity have been the physiological responses to change, local authorities and scientists may evaluate the possibilities of other forces becoming the dominant drivers of productivity (such as fire or insect disturbances). This evaluation can be in the form of a likelihood based on the current conditions of the system and current knowledge (Box 1 in **Figure 8**) and the possible change (Box 2 – **Figure 8**). This may lead to choosing an adaptation option to minimize the probability of fire occurrence, while still anticipating the physiological responses and monitoring for any signs of change. The IPCC provides a subset of possible future climate which has been regionalized for many parts of the world. As a result, a subset of plausible climatic changes (Box 2 – **Figure 8**) have been based on these regionalized projections, they can be a first step, along with the historical record, recent paleo-record, extreme events, at planning for possible future scenarios and adapted as improved projections become available.

Environmental change is only one of the possible stressors affecting forests. In this framework, the extent to which other stressors affect productivity can be integrated (such as over harvesting or where invasive species limit population size or growth). Some of the integration work has already been done for specific localities. Maps of species current distributions have been estimated for possible future conditions (Coops et al. 2007b, 2009). As well, some physiological modeling under a set of climate scenarios has also been performed (Boisvenue and Running 2010). Drivers of past productivity have been identified for many locations. Generally, it is thought that for many locations any forest management efforts would be overwhelmed by natural disturbances (Kurz et al. 2008), which may be the case in some locations. Places that have already shown loss of forest land due to concurrent decreased growth and increased mortality due to drought and fire events, such as the southwestern Unites States (Yuan et al. 2008; Ganey and Vojta 2011), may be limited in adaptation options for the region as a whole.

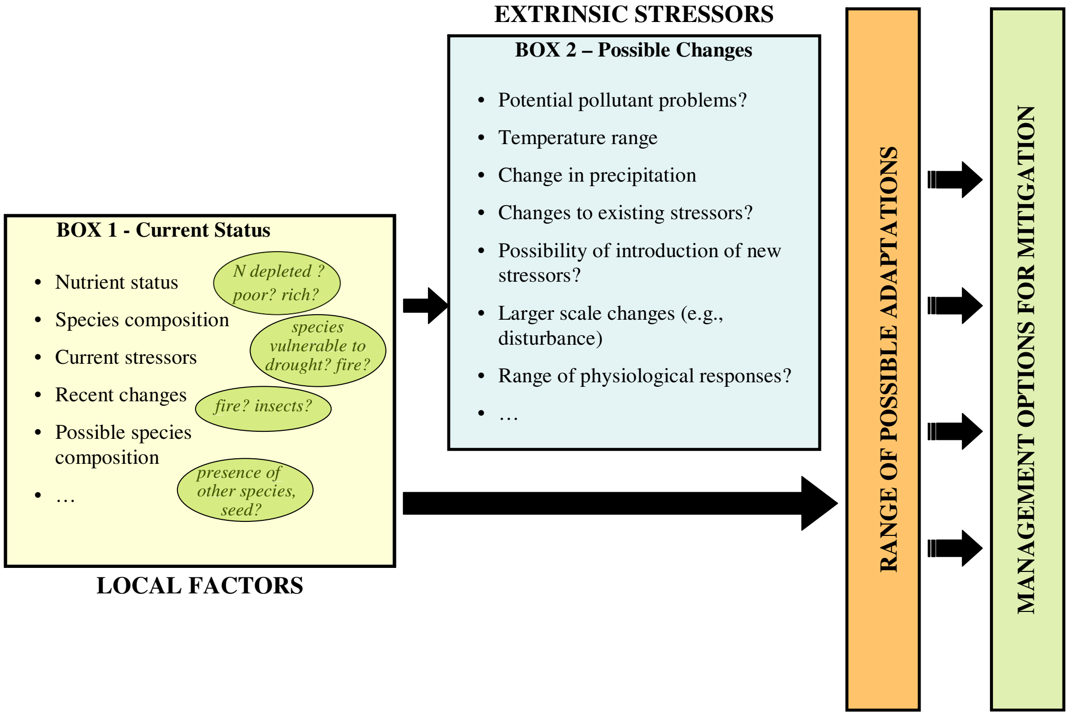
EXTRINSIC STRESSORS
BOX 2 – Possible Changes
Potential pollutant problems?
Temperature range
Change in precipitation
Changes to existing stressors?
Possibility of introduction of new stressors?
Larger scale changes (e.g., disturbance)
Range of physiological responses?
…
BOX 1 - Current Status
Nutrient status
N depleted ? poor? rich?
Species composition
species vulnerable to drought? fire?
Current stressors
Recent changes
fire? insects?
Possible species composition
presence of other species, seed?
…
LOCAL FACTORS
RANGE OF POSSIBLE ADAPTATIONS
MANAGEMENT OPTIONS FOR MITIGATION

Figure 8 A framework for developing local adaptation and mitigation options for management of forest productivity.

However, localized strategies to minimize the effect of drought and prevent fire may be able to maintain a viable forest in specific locations within the generally affected area. Many forests could be managed to adapt to changes in environmental conditions and minimize the undesirable effects of expected increases in tree mortality due to insects (Sturrock et al. 2011). In some locations, change may involve increases in intense rain or wind events, and selected strategies may include minimizing landslides or windthrow. In other areas, possible adaptations will be relatively simple, at least in the short-term assessment. For example, where a single climatic limiting factor clearly dominates, such as low-temperature constraints on the growing season at high latitudes or water limitations in dry forests, plant responses are fairly predictable. Generalist species are also more likely to do better as they are less restricted in the combination of factors required for their survival and growth. Hence, if the present species composition is dominated by generalist species, the probability of maintaining similar levels of productivity may be quite good. Other synergic factors may compound the effects of changing conditions on the ability of a species to adapt to changes environmental conditions. A simultaneous increase in fire frequency and the harvest rate might seriously compromise overall productivity. This approach assumes that localities can be flexible and adapt their selected options as the environmental conditions change and/or as the knowledge of how the system may react, increases. Unfortunately, few political organizations are presently that flexible.

4.12.4.3 Mitigation Actions

The main tools for mitigation of undesirable effects of changing conditions on forest productivity are vegetation management and mobility of services. If some options are not socially acceptable, and can be avoided, management-driven mitigation actions can be derived. If the loss of productivity is unavoidable, services provided by this specific forest may possibly be extracted from other locations (e.g., wood products) but other less-mobile services may be lost. Assisted migration programs exist. In parts of the United States and in western Canada, more southern ecotypes of trees are being manually replanted in areas where the anticipated conditions are likely to match that of the ecotype. Provenance manipulation (Griesbauer et al. 2011) and genetic and silvicultural approaches to increase adaptive capacities and to decrease climate-related vulnerabilities of forests can be based on ecophysiological knowledge. In northern latitudes, much of the genetic variation in trees revolves around cold hardiness dormancy timing and frost tolerance, so moving trees to higher latitudes or elevation may be acceptable if the regional climate warms over decadal and longer time scales. A species' distribution since the last glacial maximum may be a good indicator of a species' ability to adapt with wide-ranging species being more likely to exhibit more plasticity in their traits. Areas of increased aridity would most probably loose some leaf-area carrying capacity. Planting at reduced density in these sites may be a viable solution. For sites with increases in large-scale insect epidemics and large-scale wildfires, increasing thinning and vegetation harvesting may be an option to reduce stress and fire probability. Such an increase in biomass harvesting may even be paired with the use of the extracted material as biofuel. Once the range of possible adaptations is defined, if maintaining forests on sites is a viable option, most management actions should probably be aimed at increasing the forest resistance and resilience. Because species responses to environmental change are and will be largely idiosyncratic, managing for resilience will require monitoring and flexibility in management interventions. Indicator species and a lookout for new or invasive species may help in resilience monitoring.

4.12.4.4 Reducing Uncertainties

The uncertainties inherent to changing conditions can be diminished by conducting research, assessing risks, and linking results to forest policy and planning. Global-level monitoring efforts are essential to provide examples of local adaptation strategies, but also to prevent (or anticipate) large-scale losses and reduce uncertainties. For example, it is not yet clear if forests are losing genetic diversity. In high diversity areas like the tropics, monitoring will be required to ensure that we do not lose important genetic material (Hoban et al. 2010; Normand et al. 2011). The varied responses that have already occurred as well as our knowledge gaps about processes and how they combined through scales, justify the need for global monitoring (Körner 2004; Bugmann and Bigler 2010).

There are other identifiable ways to reduce uncertainty. First, at the stand-scale, some of the uncertainties in productivity estimates can be substantially reduced with a better quantification of fine-root turnover and litterfall, which are the two dominant NPP components, particularly in the later stages of stand development (Chen et al. 2002). Some work is underway for quantitative estimates but these must be consolidated and made available for modeling exercises. Second, there are currently conflicting results between species niche modeling and process modeling. Niche modeling predicts a decline in productivity, while ecophysiological modeling predicts more of an increase (Keenan et al. 2011). A new synergy between niche- and process-based models is urgently needed in order to improve our predictive ability of productivity. Third, the pinpointing of processes behind drought-induced mortality would also contribute to much improved predictions of vulnerability (Lines et al. 2010; McDowell 2011), and would help to incorporate drought effects into global carbon cycle models (van der Molen et al. 2011) to account for some of the feedbacks effects. Fourth, N-feedback effects should also be included in global-scale models because N is now emerging as a pivotal factor in response to global change (Norby et al. 2010). Fifth, disturbance modeling cannot be ignored in projections of forest productivity (Flannigan et al. 2005; Fleming et al. 2002). Here again, much information is available and many sophisticated modeling approaches have been applied to disturbance projections, but these projections need to be incorporated into forest productivity projections. Sixth, more of the uncertainty in climate modeling, the main input to productivity projections, needs to be taken into account in forest productivity modeling (Sushama et al. 2010, Pielke and Wilby, 2012).

Processes such as photosynthesis, respiration, plant nutrient requirements, transpiration, water relations, and other factors affecting plant growth have often been separately addressed. This has led to a better understanding of the individual processes, but integration should now be the focus of current research to show clear relationships between processes and to better understand the scaling issues necessary for assessment of the impacts of a changing environment. More linkages between experimental results and monitoring tools may compensate for some of our knowledge gaps (Polly et al. 2011; Norby and Luo 2004). Long-term global-change manipulative experiments, especially in high-priority ecosystems such as tropical forests and high-latitude regions, are essential to maximizing information gain concerning future states of the earth system. One such research effort is underway with the National Aeronautics and Space Administration in the United States (http://cce.nasa.gov/terrestrial_ecology/scoping.html).

Models are essential for assimilating data from long-term experiments and process studies, with information from long-term observations, surveys, and space-for-time studies along environmental and biological gradients. Linking data across scales has already begun (Running et al. 2004; Van Tuyl et al. 2005; Reichstein et al. 2007; Scurlock and Olson 2002; Verstraeten et al. 2006; Coops et al. 2007a; Pan et al. 2006). With new and freely available satellite data (Zhao et al. 2005) many more cross-scale linkages can be developed (Mildrexler et al. 2009). Such advances will help reduce modeling uncertainties and may contribute to deciphering cross-scale effects as well as correcting existing biases (Simic et al. 2004; Smith et al. 2011). Any climate mitigation actions will require regular reassessment and reorganization as environmental conditions change and as more or better information on the processes that lead to forest productivity becomes available. In this context of a constant flow of new information and where new analytical tools are constantly becoming available, scientists, policy makers, and land managers need to jointly develop adaptation and mitigation approaches to forested land management.

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4.13 Social–Ecological Vulnerability of Grassland Ecosystems

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4.13.1 Introduction

Grassland systems are extensively present across the globe and are a critical source of ecosystem services to societal groups on many continents. These systems are characterized by their arid and semiarid environments where rainfall tends to be too variable or evaporative losses reduce water availability to reliably support cropping systems or substantial forest cover. A number of grasslands worldwide have developed land-use practices to accommodate the variable rainfall patterns, and seasonal and spatial patterns of forage production displayed by the nomadic pastoral systems practiced in Asia and in Africa. The Americas, in contrast, have more sedentary forms of livestock production that are implemented more and more in other regions of the globe. Grasslands and other semiarid systems, globally, support over 1 billion people. These pastoral systems are dependent on grassland ecosystem services, including forage production, wool, skins, meat, and dairy products, and in many systems provide critical biodiversity and land and water protection services that serve to maintain pastoral livelihoods. Precipitation variability and associated drought conditions frequently experienced in these grassland systems are key drivers of these systems.

Due to the inherent climate variability of grassland ecosystems, they have a complex relationship to vulnerability, which depends on the scale of interest and the scope of the drivers of change. Vulnerability is defined as the degree to which a system experiences harm due to exposure to a perturbation or stress (Turner et al. 2003a,b) and can be evaluated by assessing the sensitivity and adaptive capacity of social–ecological systems to exposure to external pressures (Sietz et al., 2011). As one evaluates the vulnerability of grassland systems, there are considerations of both the biophysical nature and the social–ecological system perspectives that need to be considered. In addition, these biophysical nature and social–ecological perspectives influence the manner in which exposure and sensitivity of the system will affect the system dynamic. The ability of the social–ecological system to respond to these impacts, as determined by the exposure and sensitivity factors, will depend on the adaptive capacity of the system and the available capital assets available to the community. The resilience of the system or the adaptation actions taken under a particular stress will be determined by a combination of these factors, which vary over time and space even within a particular system under consideration. Grassland systems tend to have higher levels of vulnerability since the exposure to climate effects in numerous regions is becoming more evident, and the sensitivity to changes in moisture can lead to threshold changes in a number of social–ecological features of the pastoral and grassland systems across the globe. In addition, in many of the regions of the world the range of adaptive capacity has been altered in ways that reduce the ability of the system to adjust or to accommodate the changes these systems are facing.

The biophysical vulnerabilities are more apparent and more readily evaluated. The social–ecological view more explicitly incorporates the human dimension into the evaluation of vulnerability of the system (Kasperson and Kasperson 2001; Robinson and Berkes 2010), especially related to livelihood strategies undertaken by different communities that affect both the grassland ecosystems, and characterizes the adaptive capacity of the system to cope with change. The manner in which these climate and social–ecological factors interact across various dimensions of space, time, and social characteristics of grassland systems define different levels of vulnerability to climate and other stressors. Impacts of these changes are unequally felt throughout a community or region (Galvin et al. 2004). The level of impacts to the social–ecological system will depend on interaction between impacts on natural and human, social and capital assets of the system that groups or individuals rely upon most closely to determine decisions of livelihood strategies (Vogel et al. 2007; Galvin, 2009). Although various communities may face similar risks, they may not be equally vulnerable.

There are a number of methods to measure a group's vulnerability (Robinson and Berkes 2010; Sietz et al. 2011). Adger et al. (2001, 2003, 2006) describe vulnerability assessments that include measures combining poverty indicators with a measurement of the diversity of resources, such as household income, education level, health of children, and other factors. Other assessment methods of vulnerability combine a suite of sensitivity indicators relative to socioeconomic variability, such as food security, ecosystem,

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settlement/infrastructure, or human population health conditions (Moss et al. 2000). Measuring both ecosystem vulnerability and indicators of human vulnerability provides information on the interaction between the social and economical vulnerability of populations and the degree of resilience of the ecosystem.

This chapter explores these related factors across different grassland systems to illustrate both the biophysical aspects and the social–ecological characteristics of vulnerability of these systems. The analysis provides insights to the robust adaptive capacity these systems possess under certain situations of environmental stresses and the fragility under conditions of multiple stresses or when thresholds are crossed. These threshold changes can prevent inherent processes and social–ecological structures to adequately respond to stresses and may lead to fundamental system changes.

4.13.2 Background

Grasslands around the globe occupy ~40% or about $55.5 \times 10^6\,\text{km}^2$ of the Earth's terrestrial surface, excluding Greenland and Antarctica (Olson et al. 1983). Land-use intensification due to grazing and cropland conversion in a number of areas around the world has had global-scale impacts on carbon, water cycling, and dust aerosols (Neff et al. 2008). These impacts have local and regional impacts on human well-being and grassland productivity. Precipitation and soil water are key parameters controlling ecosystem structure and function of grassland ecosystems in arid and semiarid regions. Grassland ecosystems are particularly sensitive to the balance among factors controling water availability, including increased temperature, which directly affects evapo-transpiration (ET), changes in precipitation patterns, and altered soil water storage and elevated atmospheric CO_2 concentration (Ojima et al. 1996; Owensby et al. 1999; Morgan et al., 2001, 2004a,b, 2011). Land-use impacts have historically impacted grassland systems throughout its range in Eurasia and Americas due to the fertile soils and ease of conversion to croplands. In the coming decades, the combination of changing land use and increased aridity could enhance dust emissions and destabilize grasslands (Reynolds et al. 2001; Neff et al. 2005), unless adaptive management strategies can be employed to mitigate ecosystem responses.

In these grassland systems, plant productivity and water cycles are tightly coupled (Ojima et al. 1993; Sala et al. 1996), but this linkage depends in part on the plant functional types (Peters 2002) and can be disrupted by land-use changes and invasive species. For instance, warm season (C4) grasses take advantage of summer moisture associated with monsoon rains. Modeling and field observations suggest that transpirational (T) water loss (T/ET) is greater from grasslands than shrublands in the southwestern United States (Peters 2002; Emmerich 2007). The seasonal expression of plant metabolism and rooting depth accessing soil moisture determines some of the differences between grass and shrub functional types and differences in plant cover (% bare ground), which controls the differences in evapotranspiration. Climate affects the distribution of plant functional types that has an effect on the delivery of ecosystem services. In addition, the vulnerability of these systems may be altered by the changes in plant functional types due to changes in moisture relationships of the vegetation relative to changes in temperature and evapo-transpiration.

The sensitivity of these grassland systems to climate is associated with the lack of adequate reserves of water, low soil nutrients, and the low vegetative cover (Hulme et al. 2001; Olesen and Bindi 2002). These characteristics make these grassland ecosystems to be among the earliest ecosystems to exhibit the effects of changes in temperature and moisture (Ojima et al. 1993). In addition, vulnerability to climate variability and directional climate change of these ecosystems is accelerated by human-induced land-use changes (Ellis and Galvin 1994; Schlesinger et al. 1990; Reynolds et al. 2007). There are several ways in which changes in local and regional climate may affect ecosystem function and structure of grasslands. These effects may occur through interactions of changes in regional climatology and direct human actions including grazing management, biogeochemical direct CO_2 effects, and structural changes resulting from woody expansion or bush clearing (Morgan et al. 2001, 2011; Archer et al. 1995, 2001; Hibbard et al 2003; Parton et al. 1994).

These grassland social–ecological systems have developed to accommodate the variable rainfall patterns and extensive forage production across landscapes. Nomadic pastoral systems have emerged across all grasslands as an effective grazing system to capture dispersed ecosystem services in space and time across vast landscapes. Recently, transition of these nomadic practices has given way to more sedentary forms of livestock production and in some regions have altered the delivery of ecosystem services. In addition to these primarily pastoral systems, mixed crop systems have also developed where opportunistic crop production is deployed to augment both human and livestock food supply (Seré et al. 1996; Bouwman 2005). Changes in land use arise from changes in demographic patterns, economic incentives, market demands, production goals, and policy issues related to land ownership and market access. These factors vary across the globe; for instance, in the Eurasian steppe the recent political reorganization has led to recovery of some of the grasslands, in part due to the collapse of supporting infrastructure developed under Soviet management and the resulting decline in livestock numbers throughout the region (Ojima et al. 2004; Chuluun et al. 2005, 2008). Drought experienced during the late 1950s coupled with increased human population levels and policy decisions in Inner Mongolia have led to large scale land degradation and human suffering. Land degradation in this region of China continued into the 1990s due to intensification of grazing and cropping leading to more drastic policy regulations to reduce these pressures on the land in recent years.

It is generally difficult to separate the effect of human-induced land degradation from the effect of climate including drought. The grazing pressure in these systems is not adequately reduced at the time of onset of a major drought, and these grazing levels accelerate the degradation of the grassland system as the drought conditions persist. The combination of drought conditions and grazing pressure can lead to desertification and loss of grassland components of these landscapes.

In general, grasslands are dominated by perennial grasses and woody plants. Desert or desertlike environments are characterized by a greater presence of woody canopy cover and a replacement of perennial grasses by annuals. Grazing pressure alone can result in a switch from grassland vegetation to more woody components dominating the landscape (Archer et al. 1995, 2001). Soil erosion rates may increase as plant cover decreases leading to loss of productive potential – a process that may be irreversible, or nearly so. The rate of transition is almost always exacerbated by intense human use of the land, as occurs in most grassland and savanna regions (Neff et al. 2005, 2008; Seitz et al. 2011; Reynolds et al. 2007). Grassland degradation can thus occur through both functional (e.g., reduced primary productivity) and structural (e.g., from perennial to annual grasses or to woody encroachment) change.

In summary, social–ecological grassland systems are very sensitive to climate. First, productivity and nutrient cycling are closely tied to climate and could appreciably change with altered climate. Fairly small climatic changes could induce structural changes over large areas of grasslands. These structural changes may result from degradation of grasslands and lead to a dramatic reduction in ecosystem services and increase the vulnerability of the social–ecological system. In addition to these biophysical interactions, the sensitivity to market demands also contributes to changes in land-use practices. If these land-use practices lead to intensification of grazing levels or land-use conversion that exceeds the ability of ecosystem services to maintain or support ecosystem production, then the resilience of the system may be compromised beyond its ability to maintain grassland components of the system and may collapse (Walker and Salt 2006; Reynolds et al. 2007). When we look at the impact of climate on grasslands, it is important to assess the impacts in conjunction markets, policies, and other human activities.

The following case studies are presented to illustrate the interplay of biophysical changes under differing social–ecological systems in the Central United States (Great Plains), Eurasia (primarily, Mongolia), and East Africa.

4.13.3 Great Plains

The US Great Plains covers an area of 1.3 million km^2 in the Central United States and was historically predominantly grasslands. Large numbers of ungulates coevolved in the extensive grasslands of the Great Plains with large herds of bison, elk, and pronghorn observed across the landscapes of the Great Plains in the 1800s. Fire is a major feature in the more mesic regions of the Great Plains, with the tallgrass prairie burning, historically, every 2–3 years (Hulbert 1986; Ojima et al. 1994).

Native American populations occupied these grassland systems for thousands of years. Now, however, much of these grasslands have been taken over by settlers since the late 1800s and have converted these grasslands to croplands or large ranches. The Plains are characterized by a temperature gradient from north to south and a precipitation gradient from west to east. Annual average precipitation ranges from 200 mm in the west to approximately 1100 mm in the east and southeastern portion of the range and can be highly variable from year to year. There is strong seasonality, high variability, and frequent extreme events in the Great Plains including droughts, floods, hail, ice storms, heat waves, tornadoes, and blizzards.

Currently in the US Great Plains, the grazing industry is based on industrial and private ranching. The size of ranches is often quite large, and when cattle are pulled off of the range they are often finished at feedlots where they are grain-fed. Many ranchers also grow crops, some for sale and some for feed, so separating livestock operations from cropping operations is often difficult in the Great Plains.

Land managers in the Great Plains are concerned about a variety of factors related to climate variability and change, though often multidecadal changes in climate statistics is not the most important concern. More likely, other factors such as market or commodity prices, incentives, conservation policy, and social factors are considered in the decision making (Ojima and Lackett 2002). In fact, many operators in this region are vulnerable due to the declining economic returns from farming and ranching. Many land managers and households are operating on the economic margin, and small shifts in climate or markets may drive them out of business. There have been record numbers of foreclosures in the region in the past decade, and these farms are often being aggregated into larger operations. This is leading to population declines in the region, especially of the younger segment of the population who find it difficult to maintain a livelihood. This results in creating an older population demographic, overall, in the region. These changes in the size of operations and the demographic impacts that result have an adverse effect on the social structure of these rural areas. These trends have put pressure on rural areas, leading to a stressed system where rural towns may have problems providing adequate social services for inhabitants due to declining population numbers, tax bases, and rural infrastructure.

In the Great Plains environment, variability in weather and economic dynamics results in enhanced uncertainty in land-use decisions and the social well-being of the region. The rangeland ecosystems have proven more vulnerable to changes in precipitation patterns during the past decade. Changes in climate statistics are being experienced in various ways, such as increased nighttime temperature, increased intensity of rainfall events, extended growing season, extended drought periods, and elevated atmospheric CO_2 concentration (Field et al. 2007; CCSP 2008a). Associated changes in vegetation structure due to droughts in the semiarid ecosystems affect grassland production and the extent of shrub cover affecting the forage availability in these rangelands (Hibbard et al 2003). The potential impacts of these changes include the modified vulnerability of farm and ranch families to climate and market stresses, the modification of crop and livestock production systems, impacted water use competition, changed water quality, expansion of weeds, pests, and diseases, a change in plant–animal communities, altered fire and storm patterns, changes in grassland ecosystems, such as species composition, disruption of pollinator relationships, tree mortality, enhanced vulnerability to drought conditions, and insect or disease outbreaks (Field et al. 2007; CCSP 2008a,b).

Seasonality is an important factor affecting land systems in the Great Plains. A change in the mean is not as important to the land managers as a change in variability or seasonal patterns of change. For example, hotter temperatures and less moisture during the growing season may dramatically impact range production. Other variables identified included summer droughts, winter storms, extreme ice storms, and temperature extremes. Changes in climate statistics that affect the frequency of these events would increase the exposure to these detrimental weather impacts and increase the vulnerability of these pastoral systems, which are financially operating on a narrow margin of success.

When strictly looking at range and livestock systems, there are a number of potential impacts identified (Morgan et al. 2001, 2004a,b, 2011; Ojima and Lackett 2002). First, forage production and quality will certainly be altered. Some of the changes may be beneficial, such as enhanced production under elevated CO_2, while other changes may be deleterious, such as the fact that the forage may be less nutritious (Polley et al 2002). Carrying capacity will be impacted and there will be vegetation shifts. Increased extreme events may lead to impaired performance of intensive livestock systems if livestock thermal thresholds are exceeded (Hahn and Mader 1997). There may be changes in the irrigation water supply, which has implications for the raising of feed for livestock (Ojima and Lackett 2002).

Coping strategies that farmers, ranchers, and other residents of the Great Plains may use to deal with climate include better preparation for extreme events and multiple year events, diversification of land-use practices in cropping and livestock systems in order to take advantage of opportunities and reduce vulnerabilities, researching new storage areas for water in case new storage locations are needed in the future under a changed hydrological regime, and increasing soil organic matter in order to increase water holding capacity and soil fertility (Ojima and Lackett 2002).

When managing ecosystem services for climate and employing adaptive management practices, a number of concepts are important to understand. First, the regional context of the change is important, for instance market drivers of cashmere, land tenure policies, and community governance of grazing land access. Second, no-regrets options, such as improving grazing systems to store more organic matter and improved soil moisture. These options make sense given current conditions and that potential future options should be established. Third, people need to be provided with alternatives for adaptation, based on the adaptive capacity. Fourth, communities should learn by doing and evaluate results along the way, making the process of adaptation an iterative process that provides community engagement. And last, the public must be kept informed of the implications of change.

Analysis of coping strategies to climate in the Great Plains indicates that various aspects need to be included in the decision-making process in developing adaptation strategies. These include the following: First, vulnerability needs to be studied in the local context and needs to be measured in terms of variability and extreme events. Second, the vulnerability of currently stressed sectors in the Great Plains could be exacerbated due to changes in grassland climate. Third, land managers in the Great Plains are concerned with changes in the environment, climate, and society, as well as economic considerations. Fourth, seasonal changes to snowmelt will likely impact water storage and delivery systems in the region and residents are very concerned about a clean and reliable water source. Fifth, soil carbon management is critical to coping with climate, and conserving and building soil carbon is seen as a 'win–win' situation. And last, technological and information transfers that may help residents do not always reach the stakeholders in a meaningful way.

Many ranchers want to be part of the solution to reduce risks from environmental change (Ojima and Lackett 2002). They also want to explore opportunities that may emerge due to changes in grassland climatology, and of course to be prepared for any negative shifts. Flexible no-regrets options may help many ranchers ride out the financial ups and downs that are the norm in today's market to stay in business. Coping strategies include better forecasting and preparation for extreme events and multiple year events, land conversion and changes in enterprise, new or improved grazing systems, efforts to understand pest and disease vectors, development of better communication at all levels (scientists, end users, and policymakers), and diversification of land-use practices in cropping and livestock systems.

Management strategies that lessen the impacts of the changing grassland climatology on domestic livestock and people in the Plains are needed. Strategies to reduce vulnerability of domestic livestock include changes of the mix of livestock raised, change of breeds of animals, change in genetics of livestock, change the seasonality of production (e.g., calving, lambing, weaning), and incorporation of technologies to reduce stresses and pest on animals. Strategies that may reduce livelihood vulnerabilities include diversification of operations and increased access to diverse landscape types. The adoption of public policies to deal with climate and the development of improved system-level management can also provide additional guidance to operators, which provide greater resilience to extreme events (possibly more frequent or longer) and include considerations for increased feed reserves, enterprise diversification, improved weather forecasting, increased water reserves, and tactics for dealing with hot temperatures in intensive livestock operations.

Overall, there are five points that characterize the Great Plains today (and reflect characteristics common to other regions around the world, as well):

1. Vulnerability needs to be measured in terms of variability, extreme events, and economics. Both the economics of implementing coping strategies and the seasonality of changes are important in assessing the vulnerability of people in the Plains.
2. Land managers in the Great Plains are concerned with changes in the environment and climate, as well as economic considerations. They are also interested in skillful climate forecasts for other regions that produce products that compete with products from the Great Plains.
3. Technological and information transfers do not always reach stakeholders. There is a communication gap that needs to be improved in order to keep stakeholders informed on plausible changes and options.
4. The vulnerability of currently stressed sectors in the Great Plains will likely be exacerbated. For the many farmers and ranchers in the Plains who are already on the edge, slight detrimental climatic changes could push them over the edge.
5. Seasonal changes to snowmelt in the Rocky Mountains may impact water storage and delivery systems. This has important implications for irrigation and stock water.

4.13.4 Mongolian Example

The Mongolian grasslands have a diversity of ecosystems, ranging from forest-steppe in the north to the Gobi desert-steppe in the south, and the steppe ecosystem dispersed in between. The Altai Mountains in the southwest, the Khangai Mountains, and the Khentii Mountains in north-central part of the country add to diversity of landscape, habitat, and resource availability. The Mongolian nomadic pastoral cultures occur as an emergent feature of the variable ecosystem dynamics of the arid and semiarid systems. These pastoral systems have adapted to variable environmental conditions responding to seasonally available resources across various landscapes ranging from river valleys, meadows, steppe, and mountain valleys. The emergence of hierarchical pastoral networks or cooperative groups based on a common location of natural resources or family relationships, as a complex adaptive system, increases the resiliency of these systems to climate variability.

Throughout history, nomadic herders in the Eurasian steppe have both formally and informally organized themselves, or have been organized, into a rich variety of societies. At the smallest level, livestock production has always been carried out around a range of customary institutions that perform social, political, and economic functions: the household, the camp, and the neighborhood. Throughout the period of radical changes that have occurred in the Eurasian steppe region, from feudalism through socialism to the emerging market system, these most basic of institutions have survived in one form or another in Mongolia.

Traditional pastoral networks evolved in the direction to increase human adaptive capacity to cope with climatic risks. Spatially large landscapes are critical in arid lands to offset climate variability with extreme events such as winter storm events (*zud*) and droughts. Interaction between ecosystems and nomadic land-use systems coshaped them in mutual adaptive ways for hundreds of years, thus making both the Mongolian rangeland ecosystem and the nomadic pastoral system resilient and sustainable.

In addition, the cultural landscape design of the nomadic pastoralists of Mongolia developed so that seasonal movement of livestock was coordinated among the various communities and tribes. The nomadic pastoral system took advantage of the winter forage areas of the mountains where snow was available for watering the livestock and the herders and winter forage available from the previous summer's growth. Movement to the valley as spring emerged took advantage of the early emergence of forage along streams, and later summer movements sought forage in valleys where moisture from seeps and springs provided good pastures.

These pastoral traditional networks have emerged with an understanding of the variability of resources in time and space and tend to maximize forage accessibility under these variable conditions in the Mongolian steppe (Chuluun 2000; Ojima et al. 2004; Chuluun et al. 2005; Chuluun et al. 2008; Ojima and Chuluun 2008). The most mobile herders are associated with drier parts of the steppe and the Gobi areas where nonequilibrium grassland ecosystem dynamics are observed (Fernández-Giménez 1999). The herders from these regions move to places where better rangeland conditions exist–especially during the summer season. Currently, their movements are constrained to administrative boundaries, rather than to the ecological extent of suitable rangelands.

The fragmentation of the cultural landscape due to political reorganization of the local political boundaries in the grassland systems of Mongolia has increased vulnerability and reduced the adaptive capacities to cope with climate variability of traditional pastoral systems. During the collectivization or *negdel* period between 1960 and 1990, herders were moving less frequently, but across longer distances with support from the centralized government providing mechanized transport (e.g., trucks and tractors). The pastoral collectives and the state assigned new administrative territories that cut across lines of traditional nomadic movements. Within these collectives were several smaller units or teams, which were the levels at which herding activities were allocated and was comprised of one or two households (Mearns 1993). Although these traditional functions may have been subsumed by the collectives, the customary institutions did not disappear altogether, as is demonstrated by the fact that many are now reemerging. However, herders still kept the traditional pastoral land-use concept. Herdsmen were commonly organized into collectives and were allowed only a small number of animals for private ownership (Sneath 2003). The provincial and national government established a strategy for short-term, long-distance moves (*otor*) to safeguard against drought and rangeland overuse. This strategy also served as a mechanism to fatten the stock in the summer and fall seasons. The collectives made all decisions over allocations of animals and specialization in tasks and species. Although these functions may have been subsumed by the collectives, the customary institutions did not disappear altogether, as is demonstrated by the fact that historic community structures have reemerged such as the 'hot ails,' referring to people from one river or one well, or people from one living area and is result of adapting to particular kind of environment in Mongolia, during the transition to a market economy (Schmidt et al. 2002; Janzen 2005; Schmidt 2006; Reading et al. 2006).

Negdels or collectives were dissolved with the privatization of livestock in the early 1990s. Since the decollectivization started in the early 1990s, pastoral movement became less frequent and shorter due to the lack of subsidies to maintain transportation for long-distance travel and preference to stay closer to settled areas and water source areas (Janzen 2005; Fernández-Giménez 2006; Reading et al. 2006). The higher concentration of livestock near settled areas and year-round use of riparian zones have led to deterioration of the rangelands (Ojima et al. 2004; Janzen 2005; Chuluun et al. 2005).

4.13.4.1 Current Conditions

Mongolia is in a region that has experienced, during the past century, one of the highest surface warming on our Earth. In terms of climate influences on pastoral systems, during the last 70 years the annual mean air temperature has increased by over 2 °C in Mongolia (Batima et al. 2005; Dagvadorj et al. 2009) and this warming has intensified during the last two decades. Winter temperature has increased by 3.6 °C and spring and autumn seasonal temperatures by 1.5 °C. However, the summer temperature has decreased by 0.3 °C during the past 70 years. Changes in warming are not spatially uniform; winter warming is more pronounced in the high mountains and mountain valleys and less in the Gobi desert and the steppe. Annual precipitation has not changed much, but seasonal patterns of rainfall have changed with the spring season becoming drier, causing decreased plant biomass production and later plant onset in some parts of Mongolia. Frequency of zud (drought in summer followed by cold snowy winter) has increased. Regional warming is also reducing surface water, lowering underground water levels, and decreasing snow covered days with consequences of black zud (winter drought conditions).

In addition, socio-economic and climate conditions of the past 50 years are affecting these systems in dramatic ways. Throughout Mongolia, large changes in environmental, demographic, political, and economic driving forces during the past half century have affected pastoral systems. Since the period of intensive Soviet influence following WWII to the present, the general trend has been toward a greater intensification of resource exploitation at the expense of traditional patterns of extensive range utilization. These socio-economic factors are overriding the effects of any changes in climate statistics on pastoral productivity during the past 20 years of social transition. Thus, climate–land use interactions are being modified by these market and policy changes, which is contributing to the overexploitation of forage production, water availability, and other ecosystem services. Since 1990, political changes and opening of markets have led to modifications in pastoral management due to relaxation of central government controls, privatization of livestock, and access to ‘free-enterprise’ and open market systems. This shift to a free-market economy has led to changes in the livestock sector such as more intensive stocking rates in localized areas, especially around water facilities and villages, and change in animal breeds used. In addition, a more sedentary grazing system has emerged due to the lack of government support for long distance movements of animals and restricted boundaries associated with grazing permission in the current village level grazing systems. These land use changes and greater vulnerability of the pastoral systems associated with livestock losses, increased stagnation of grazing enterprises in rural civic centers, and observations of rising unemployment have led to increased poverty among households and related decline in social services in these civic centers. Although livestock was privatized in rural areas and the number of livestock increased, the livestock industry has suffered due to degradation of pasture and unfavorable climate conditions in recent years (MNE 2001, 2006; MHDR 2011)(e.g., severe weather conditions in 1999–2002 and in winter of 2009–10). As a result, livestock, the source of income for livelihoods of rural citizens, shrank in size and poverty has increased, in general.

Response of pastoral systems to political and economic changes, associated with incentives to sell cashmere, has led to a tripling of goat numbers and a reduction in cattle numbers across Mongolia. This has resulted in both socio-economic and ecological consequences. These changes in pastoral management coupled with climate have increased the degradation of grassland resources. Thus, we expect climate–land use and cover relationships to be crucially modified by the socio-economic forces mentioned above. Nevertheless, the complex relationship between climate variability and pastoral exploitation patterns still form the social–ecological framework for overall patterns of land use.

A key factor in this modification is the continued decline in the number of water points from year to year. Nomadic pastoral seasonal grazing patterns have been disrupted with the loss of these watering points. The increased grazing pressure around the remaining water points has resulted in overgrazing of pastures. In addition to these grazing effects, a warmer and drier climate has created conditions promoting grassland degradation. The forage availability, determined by remote sensing data from 1982 to 2002 in the central parts of Mongolia was affected by these climate effects (Ojima et al. 2004). Ellis and others (2002) showed that the steppe area adjacent to the Gobi region is especially vulnerable to climate and with increased grazing pressures during the past decade have led to desertification. Riparian ecosystems appear to have keystone value in coupled pastoral social–ecological systems. The collapse of these critical ecosystems’ ability to provide water would greatly impact the pastoral community, as water is the most valuable resource for both people and animals in drylands.

Cultural patterns of livestock movement have changed during the past two decades that has increased the vulnerability of these pastoral communities to climate. Environmental degradation has markedly increased in Mongolia and is associated with increased livestock numbers and reduced mobility of herders. Accompanying these trends is a decline in social services available in these villages. Numerous small administrative units or villages became less viable due to a lack of economic and resource support from the central government. Acceleration in desertification has occurred in part because of human influences and in part from changes in the grassland climate. As the number of livestock exceeded pasture carrying capacity, a number of impacts have been observed. These include pastureland degradation, plant production decline, occurrence of ecosystem breakdown, loss of watering holes, and a shift of grasslands to more desertlike conditions. In some areas, soil deteriorated and sand migration increased as bushes and trees, which are the main factor for arresting sand migration, were cut for local use.

4.13.5 Coping Strategies

Ironically, the extent of rangeland vulnerability today in Mongolia is far greater since the transition from a centralized to a market economy. Land degradation due to overgrazing has intensified near cities, areas of concentrated infrastructure, and water resources since the early 1990s. Traditional land-use strategies operated across larger spatial scales (cultural landscape) are in danger of being lost without access to larger cultural landscape elements that allow for seasonal grazing. A reduction in the spatial scale of the cultural landscape has led to reduced resilience and increased vulnerability of the coupled human/environmental systems.

A key to reducing this vulnerability is to enhance the resilience of communities (Walker and Salt 2006). Interestingly, cooperatives based on traditional pastoral networks are reemerging in Mongolia in response to the drought and extreme winter conditions of 1999–2002. The comparative study of pastoral communities shows that a pastoral community with cooperative structures based on traditional networks has lost less livestock compared with other communities during the recent climate disaster (Chuluun and Enkh-Amgalan 2003). Today, the Mongolian rangelands are at the bifurcation stage between two pathways: predominantly private land ownership or traditional land-use culture operated by pastoral communities. It appears that enhancement of pastoral communities based on traditional resilient pastoral networks will lead to a reduction in the future vulnerability of Mongolian pastoral systems.

Finally, the development of the modern cultural landscape of the Mongolian rangelands includes the strengthening of pastoral traditional networks with the introduction of modern technologies such as wireless communication, renewable energy resources, access to appropriate livestock breeding, use of veterinary practices, and access to markets of more finished products. Further development of early-warning systems will reduce vulnerability to extreme climate events through the incorporation of integrated technologies such as remote sensing and modeling to provide improved assessments and forecasting capabilities. There is a good probability of success if such innovative approaches to sustainable development of these natural–cultural landscapes can be implemented and lead to conservation of the critical natural–cultural landscapes of the region.

4.13.6 East Africa Example

Eastern African grassland systems provide an additional view of social–ecological vulnerability due to changes in policies, socioeconomic factors, land access, and climate (Galvin 2009; Galvin et al., 2009). Traditionally, pastoral land-use systems in Eastern Africa have adapted to rainfall variability across grassland landscapes in the region for perhaps thousands of years (Pratt and Gwynne, 1977). Wildlife and pastoral movements have made seasonal treks over vast distances to reduce risk and to take advantage of the elevation and spatial heterogeneity of forage production and availability of water resources. These movements reduce risk by reducing exposure to climate risks, enhance access to food and water resources, and access resource heterogeneity in space and timing of availability (Reid et al. 2008, 2009; Western et al. 2009; Robinson and Berkes 2010). Policy changes have restricted the movement of many pastoralists and the result has been enhanced degradation of these resources and increased vulnerability to climate (Homewood et al. 2009).

East African pastoral systems take advantage of the rainfall heterogeneity that characterizes the East African climate (Ellis and Swift 1988; Ellis and Galvin 1994). Pastoralist and wildlife movement patterns are associated with regional resource availability during the wet and dry seasons. Recent trends in land fragmentation associated with privatization and more sedentary pastoral practices in the region contribute to restricting these pastoral movement practices traditionally employed in the past (Reid et al. 2008). These recent trends of land tenure, use, and protection are leading to increased vulnerability of these pastoral communities and the natural resource base these traditional systems have evolved to respond to (Galvin 2008; Galvin et al. 2008; BurnSilver et al. 2008; Western et al. 2009).

In the Ngorogoro Conservation Area (NCA), restriction of the pastoralists's movement onto the Serengeti Plains due to conservation policies has led to reduced access to forage in the dry season. This reduced movement has increased the degradation of grassland resources in the area and has affected access not only to food resources but also to critical water resources (Galvin et al. 2008). In addition, prolonged stay in the highlands has resulted in the increased exposure to tickborne diseases and other pests reducing the health and productivity of livestock. Conservation policies have also resulted in increased competition between wildlife and livestock and tourism for water. Massive cultivation at the edges of the NCA has led to potential impacts on wildlife corridors (Boone et al. 2008).

Livelihood strategies are also being affected throughout east Africa, with more pastoralists transitioning to farming and converting grasslands to cropland or mixed livestock-cropping systems (Little et al. 2001). Increased reliance on farming in areas of extreme weather variability coupled with a decreasing livestock to human ratio is resulting in degrading social–ecological conditions.

The vulnerability of grassland has been characterized by a number of recent analyses in the region (Galvin et al. 2008; BurnSilver et al. 2008; Robinson and Berkes 2010), and these studies identify a set of factors exacerbating the situation. These factors include (a) greater population density, (b) overuse of surface water resources, (c) intercommunity conflicts, (d) expansion of unpalatable grasses, and (e) policies restricting access to grazing lands (Galvin et al. 2008; BurnSilver et al. 2008). Past strategies for coping with stresses resulting from these pressures are no longer viable, and the continued grazing pressures due to restrictions in mobility are resulting in greater loss of grassland productivity and increased poverty among the pastoralist communities. The interaction among these factors can also lead to cascading effects, further contributing to poverty among the pastoral communities, and increased degradation of natural resources. For instance, drought-induced losses of livestock, especially loadbearing animals such as camels, have resulted in reduced movement of pastoralists in northern Kenya and more reliance on pasture near watering holes (Robinson and Berkes 2010). Camels are used to carrying water to distant landscapes that have available forage, and the loss of this transport mechanism necessitates that livestock need to be closer to water supply points despite having less favorable forage availability. This overusage of forage and water resources leads to further degradation of these natural resources and contributes to increased poverty of these pastoral communities. The inability to utilize these movement strategies due to land privatization and land-use changes has resulted in social changes among pastoralists (BurnSilver et al., 2008; Western et al. 2009). The increased level of poverty and social breakdown of these pastoral communities has led to a condition where there are less community members able to provide relief to other members of the community.

4.13.7 Monitoring and Assessment Strategies for Grassland Ecosystems

There are a number of indicators of grasslands under stress as well as methods to characterize a system that has undergone biophysical changes related to climate and land-use impacts (Herrick et al. 2010; Buenemann et al. 2010). These indicators reflect changes in biological factors (e.g., species composition, change in production patterns), physical structure (e.g., woody encroachment, soil moisture changes), biogeochemical processes (e.g., nitrogen fixation, N emissions), biophysical fluxes (e.g., dust events, evapo-transpiration rates), disturbance regimes (e.g., fire frequency, grazing dynamics), and social losses (e.g., collapse of pastoral productivity, livestock production). Forecasting technologies have advanced, which incorporate field studies, social–economic surveys, remote sensing, and modeling systems to provide the effects of changes on ecosystem productivity and well-being (Boone et al. 2011; Thornton et al. 2006, 2007; Galvin et al. 2009). These systems have been deployed in regions in Africa and Asia.

Our understanding of land-use decision-making processes provides a foundation for evaluating the interactions between factors influencing human activities and their effects on ecosystem services. The environmental context of the system can be determined by the state of ecosystem services and the reliance of the decision maker on these services. Instability in the system may arise when unforeseen loss of an ecosystem service occurs, such as soil stability during a drought resulting in a massive dust storm or lack of water flow leading to desertification or drying of water bodies. The effect on the coupled human–environment system may rapidly appear, although the underlying changes have been occurring over time, undetected until a critical threshold has been met.

Research efforts have recently brought greater attention not only to the role ecosystem services have on the provisioning of key economic goods, but also in the services that sustain, regulate, and support life on Earth (Costanza et al. 1997; Daily 1997; Daily and Ellison 2002). Grassland social–ecological systems provide a wide array of goods and services upon which pastoral well-being, even survival, depends. Whereas consumptive goods provided by land systems, such as forage, grains, animal protein, and fiber and wood products, are typically valued through well-developed markets, the contributions to society and ecosystem functioning of the 'underpinning' services provided by ecosystems often remain 'invisible' and unvalued (or undervalued) and the linkage to social dynamics are rarely considered. The array of such services is broad, from those services that regulate critical human–environment processes (e.g., climate, disease, flooding, detoxification) to services that support economic activity (e.g., soil formation, primary productivity, nutrient cycling, pest control, pollination).

Understanding effects of use of land resources is dependent on being able to better incorporate ecosystem services into the decision-making process. In addition, evaluation of changes in the state of ecosystem services (i.e., maintaining soil fertility, supplying water resources, and food and fiber production) will be important to the development of the appropriate coping or adaptive strategies under different human–environment stresses. The case studies described above provide an illustration of the interactive role that social, biological, and physical components of coupled human–environment systems play. These case studies enable us to better understand the interactions of the social–ecological factors determining the vulnerability or resilience of these systems to different scenarios of social and environmental conditions.

Characterizing and determining these ecological thresholds are challenging to resource managers and to pastoral decision makers due to the sudden and often irreversible nature of these changes in ecosystem services and the novel states that emerge (Hobbs et al. 2006). Some examples of changes in the social–ecological systems due to climate and management changes from our case studies include:

- Declining water availability, local overgrazing, reduced well-being of livestock and pastoralists
- Sedentary land-use practices leading to lack of access to water and forage resources, resulting in overuse of resources and change in land-use systems
- Market pressures and demographic patterns leading to loss of pastoral livelihoods

Socio-ecological thresholds due to environmental and socio-economic drivers are being triggered in many grassland systems around the globe. Many of the basic understanding of where and when a threshold will be crossed is still unclear (Julius et al. 2008). However, the inherent sensitivity of the grassland system to climate variability and to various land-use changes has been documented (Ojima et al. 1993; Parton et al. 1994; Archer et al. 2001; Reynolds et al. 2007). The fragmentation of landscapes and the discontinuity of landscape processes also contribute to ecosystem and biodiversity vulnerability in ways that contribute to triggering social–ecological thresholds (Ojima and Corell 2009; Chuluun et al. 2008; Galvin et al. 2008).

Assessing social–ecological vulnerabilities can be conducted using various approaches (Adger and Kelly 2001; Adger et al. 2011; Moss et al., 2000). These approaches provide a framework to better correlate social outcomes, such as poverty reduction, against measures of capital assets or other measure of available resources. Other approaches take measure of societal needs, such as food availability, water access, health care, schools, and other services, which are evaluated relative to various factors such as commodity price volatility or climate variability. These approaches call for better integration of environmental and societal metrics to evaluate social–ecological vulnerability. The choices of coping strategies are determined by the capital resource assets (i.e., natural, human, social, financial, and built capital) available to different community members in a particular location and stage of societal development. Decisions are based on multiple criteria related to various cultural and economic goals for various communities (Tschakert et al. 2007). Regional decisions to cope with stress and to overcome vulnerable conditions will reduce the impacts of these stresses and make decisions that will benefit some and differentially affect others.

Monitoring of key climate characteristics related to temperature maxima or minima, seasonality of precipitation patterns, and interactions among climate characteristics will provide greater forewarning of impending critical thresholds in currently unaffected ecosystems. A number of ecosystem services can also be monitored to assess the impacts of change to society.

Critical to knowledge about ecological thresholds is a prognostic capability to better utilize, in an integrative fashion, a suite of observations in a way that a social–ecological forecast can estimate the probability of a threshold being crossed in one or more system processes (Walker and Meyers 2004; Hobbs et al. 2006; Lyytimäki and Hildén 2007).

Complex multidimensionality of ecological thresholds can be resolved through the use of integrative modeling and analytical approaches (Boone et al. 2011; Thornton et al. 2006; Reynolds et al. 2001). Development of a threshold prognostic or ecological forecasting tool to evaluate probabilities of achieving a threshold event would be extremely helpful in managing natural resources and developing adaptive management strategies to maintain ecosystem services.

4.13.8 Opportunities and Challenges for Managing for Change in Grassland Systems

Grassland ecosystems are being affected by multiple stresses and these effects are impacting society, biological communities, and ecosystem services in novel ways (Hobbs et al. 2006). As illustrated in the case studies presented here, unintended consequences arise from policy or market changes affecting pastoral decision making without considering concurrent environmental trends, such as any changes in grassland climate. Some of these impacts may only have temporary disruptions, but in some cases, such as conversion of grasslands to croplands, loss of water supplies, or changing livestock mixtures, have pushed these systems toward critical thresholds. Such system dynamics are indicative of complex adaptive systems and therefore are not easily managed to meet the multiple-state characteristics of human–environmental systems. An optimal management approach may, in fact, be counterproductive to development of a more robust adaptive management approach that recognizes the existence of multiple states and the importance of change as a basic component of the system dynamic (Berkes and Folke 1998; Gunderson and Holling 2002; Walker and Meyers 2004; Tschakert et al. 2007). Hence, an integrated decision-making framework for adaptive management scaled to the issues confronting managers and decision makers is needed. A critical aspect of the information needed is the scale of climate information necessary to make decision of plausible changes to resources.

Management options to reduce vulnerability of grasslands to climate and other social–ecological changes affecting grassland ecosystems need to incorporate research and management perspectives to deal with the dynamic nature of change they experience (Joyce 2009; Robinson and Berkes 2010; Sietz et al. 2011; Adger et al. 2011). The feasibility of these management actions will depend on the adaptive capacity of the social–ecological system and the linkages between natural resources, ecosystem services, and social–economic conditions (Joyce 2009; Adger et al. 2011). The framing of management actions need to clarify metrics and goals for management in ways that can better identify thresholds that would impact the grassland ecosystem (Adger et al. 2011).

Approaches suggested include the involvement of stakeholders at multiple scales in order to address multiple scales of changes in the social–ecological system, develop a coordinated way of implementing policy and management decisions affecting livelihoods and ecosystem services of the grassland ecosystem, and implementing adaptive management practices and monitoring schemes that are responsive to temporal and spatial dynamics of the grassland resources and pastoral communities (Joyce 2009; Robinson and Berkes 2010; Adger et al. 2011). This integrative approach will facilitate the incorporation of uncertainty and risk assessments, link modeling analysis and decision making at appropriate spatial and temporal scales, and provide a mechanism for sharing resources and knowledge across affected communities and planners (Joyce 2009).

A number of key elements are used, including identifying specific concerns of the community and for issues the community faces within the prescribed socio-environmental context. Scale of analysis in space and time can be set at an appropriate level with assistance of the stakeholder community (e.g., multiple public and private decision makers and managers and information brokers). Often, time scale needs to be matched to various issues that respond at different scales, such as rainfall at certain times of the year, heat waves at critical times of plant development or livestock production, or other climate triggers that affect maintenance of infrastructure or affect delivery of ecosystem services. Identifying the critical time scales of decision making becomes an important component of the adaptation strategy framework to ensure that appropriate climate and other information are provided. Development of the appropriate scenario information from different climate projections that are more aligned to the critical management or decision-making issue to the given situation is a fundamental consideration. The final step is to design a multidecadal strategy to deal with possible changes in climate and its effects on the socio-environmental system. This course of planning is thought to be recursive in nature. That is to say, it should be revisited every few years or so. Incorporated into this framework is the need to frequently update information regarding changes in the system.

4.13.9 Summary

Grasslands exist in regions with variable precipitation and due to moisture and temperature limitations may not provide suitable conditions to maintain cropping systems on a regular basis. These ecosystems continue to nurture a large diversity and number of ungulates, which are valued for their vast quantity and the role these animals play in maintaining these ecosystems. Humans have thrived in these environments depending on the ecosystem services for food, energy, and shelter for many thousands of years. Despite environmental variability, land-use systems have been devised to accommodate these vagaries in moisture availability. However, as we view these systems today across the globe, we see social–ecological systems that are increasingly vulnerable due to increased stress, human pressures, and climate changes.

In these grassland systems, traditional land-use systems have taken advantage of the variability in space and temporal availability of ecosystem services by developing nomadic utilization wildlife, livestock, water resources, and forage. Increased human pressures coupled with policies restricting movement of people and animal resources have led to more sedentary livestock production. The sedentarization of land use in these systems has resulted in overexploitation of accessible grassland ecosystem services. This has led to increased degradation of these ecosystems, through overgrazing, draining of shallow aquifers, and loss of biodiversity. The combined effect of these changes has led to increased vulnerability of the social–ecological systems that have emerged. The set of social–ecological examples provided here for North America, Mongolia, and East Africa demonstrate the growing vulnerability of these systems under increased human pressures, inappropriate responses to market forces, increased variability and changing seasonality of the climate system, and the restriction of movement to better accommodate environmental variability.

Adaptation strategies to deal with these enhanced vulnerabilities across these different regions will necessarily take on different pathways due to their local social–ecological conditions and the current adaptive capacity of the system under evaluation. However, there are various principles that have emerged to develop place-based strategies. These include participatory methods to codevelop goals and means to meet these goals, framing strategies within a multicriteria framework, appropriately evaluate and utilize capital resource assets to enhance resilience where possible or to assist in making adaption actions work, and last, to manage for change.

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4.14 Sea-Level Rise and Coastal Ecosystems

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Glossary

Asset Any item of value that potentially is exposed to hazards; can include buildings, other infrastructure, human beings, ecosystems, etc.

Coastal zone The potentially wide area between the dry land above the littoral and the shelf margin.

Hazard A potentially harmful event.

Local sea-level The vertical distance between the sea surface and land surface.

Global sea-level The global average of local sea-level.

Resilience The ability of a system to absorb disturbance while retaining its basic function and structure.

Risk The probability that a hazardous event will cause a certain damage to an asset.

Vulnerability Characteristic of an asset to experience damage if exposed to a hazard.

4.14.1 Introduction

Coastal ecosystems provide important environmental, social, and economic service functions. Coastal habitat and ecosystems are generally some of the richest areas for biodiversity. These systems are adapted to the various compartments that typically occur in the wide coastal zone between the hinterland and the shelf margin. Coastal wetlands include marshes, swamps, and other plant communities that are flooded part of the time, and that are hydraulically connected to the sea. Located at the interface between land and sea, tidal marshes provide unique ecosystem services for waste treatment, biological productivity, and regulation of disturbances.

Small changes in Local Sea Level (LSL) can lead to significant changes in some of these compartments posing extreme challenges to the ecosystems, particularly if these changes take place rapidly. LSL changes depend on both changes in sea surface height and land surface height. Tectonic uplift and land uplift due to postglacial rebound reduce local sea-level rise (LSLR), while local subsidence will accelerate it. In combination with changing weather extremes, changes in LSL could modify the pattern of coastal inundation with severe impacts on sensitive coastal ecosystems. The process of inundation leads to both the conversion of dry land to wetland and the conversion of wetlands to open water, thus destroying coastal habitats or forcing the ecosystems to migrate inland. However, coastal protection often inhibits migration, and a loss of valuable ecosystems would be inevitable.

Local sea-level rise would also increase the destructive force of coastal storms, leading to increased coastal erosion and an acceleration of ecosystem losses. Increased erosion would likely amplify the effects of LSLR. As a consequence, the total shoreline retreat could be much larger than suggested by present-day topography. Globally, the combined effect of LSLR and erosion could be devastating. For example, an average LSLR of 1 m along the coasts of Bangladesh would inundate 17% of the country (Titus 1990), 20% of the farmland in Egypt is below 2 m of current sea-level, and many other coastal areas would face large erosion (Figure 1). Any LSLR would also shift the tidal zone and areas inundated during storm surges further inland, with the speed of this shift depending on the local topography and the speed of the LSLR.

The vulnerability of coastal wetlands to LSLR depends on many factors, such as the coastal topography, the tidal range, and human interferences such as coastal protections and development. Depending on these factors, coastal wetlands may compensate for LSLR by vertical or horizontal migration, if the speed of change does not exceed the capability of the

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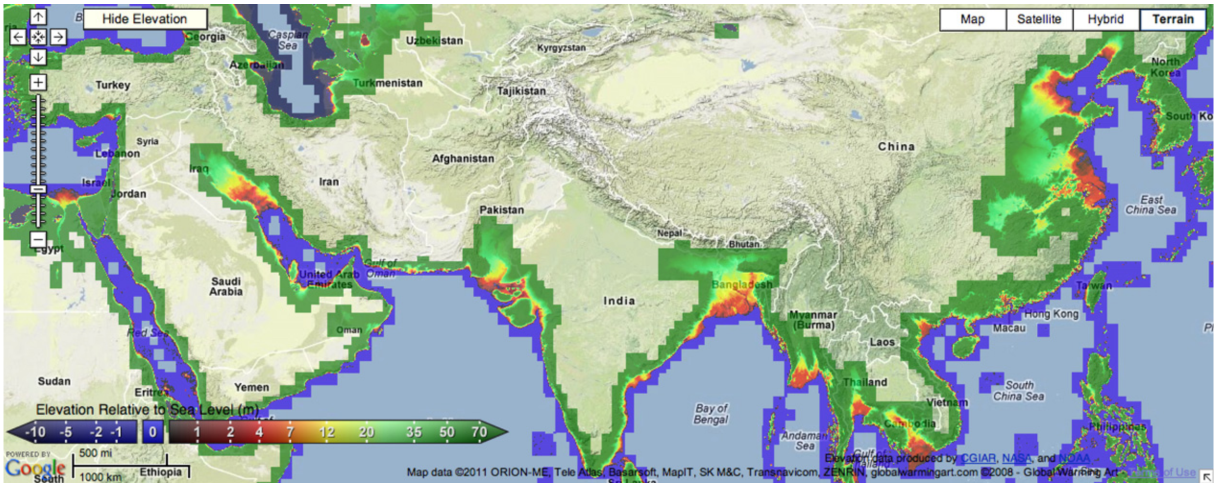
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Myanmar (Burma)
Hong Kong
Macau
Oman
Laos
Red Sea
Sudan
Eritrea
Yemen
Thailand
South China Sea
Bay of Bengal
Vietnam
Cambodia
Philippines
Andaman Sea
Elevation Relative to Sea Level (m)
-10 -5 -2 -1 0 1 2 4 7 12 20 35 50 70
POWERED BY Google
500 mi
1000 km
Ethiopia
Elevation data produced by CGIAR, NASA, and NOAA
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Figure 1 Coastal areas in Asia that are at risk of inundation. The color code of the map indicates elevation above current sea level. Most areas below 2 or 3 m are at risk of inundation from storm surges, and the probability of inundation and erosion during storm surges will increase dramatically if LSL rise in these location. Areas below 1 m are likely to be permanently inundated if LSL rise by 1 m at these locations. Graphics produced with the tool available at http://www.globalwarmingart.com/wiki/Special:SeaLevel.

ecosystems to migrate. In general, a rise of LSL leads to a reduction of terrestrial influence and an increase of marine influence. However, the changes depend strongly on coastal topography and do not linearly increase with the LSL change (Craft et al. 2009). In areas with large tidal ranges of 2 m or more, tidal marshes are less susceptible to LSLR than in areas with small tidal variations. If sediment supply allows tidal marshes to migrate vertically, then LSLR can be compensated to some extent. In some coastal areas, an LSLR would result in submergence and significant reductions of tidal marshes, while in other areas, salt marshes may transgress landward and in this process replace tidal freshwater and brackish marshes. A possible decline in the area of tidal marshes area and the conversion of habitats would impact the delivery of ecosystem services provided by coastal wetlands.

Coastal zones are attractive to humans for a variety of reasons. Besides a significant migration trend in human population from rural to urban areas, a migration into the coastal zone is taking place, increasing the pressure on coastal environments. During the last several decades, human interaction has reduced coastal wetlands globally by more than 30%, and more than 35% of the mangroves have been lost during the last 20 years (Gilman et al. 2006a). Any LSLR will add stress on top of this on-going human alteration of the coastal zones. In many areas, coastal protection in response to LSLR will further acerbate the stress.

Regional changes in weather patterns, melting of ice sheets, and increases in ocean heat could lead to significant global sea-level rise (GSLR), and assessments of the potential impact indicate possible extreme costs particularly for urban coasts (see Plag and Jules-Plag 2012). Very few assessments have focused on the economic impact of sea-level rise associated with ecosystem loss through inundation, erosion, and other sea-level related processes. Examples of a few exceptions are studies of potential sea-level rise impacts on the Everglades in Florida (Madden and Goodin 2007), on the vast coastal area and flood plain zone in Bangladesh (Sarwar 2005), and on mangroves (Gilman et al. 2006a,b). The development of policies for adaptation and mitigation of sea-level rise related impacts is also mainly focused on urban coastal areas. As a consequence, coastal ecosystems would likely be in a triple-loss situation: human alterations are leading to degradations and loss; sea-level rise would increase stress and require ecosystem migration; the human response to sea-level rise would increase coastal alterations and add stress.

IPCC prediction of the 21st GSLR displays a large range ranging from a few centimeters to 1 m, but many climate change assessments conclude that Global Sea Level (GSL) will only rise on the order of 0.5 m by the end of the twenty-first century (e.g., Bindoff et al. 2007), although it is often stated that larger values cannot be excluded (e.g., Church et al. 2010). However, studies of paleo-records indicate that there is no scientific basis to exclude GSL changes of 2 m or more within several decades. This renders model predictions unsuited as a basis for the planning of adaptation. Taking into account that LSLR can deviate more than ±100% from the global average, this implies that changes of several meters within a few decades are within the possible range of LSLR. Superposing this potential LSLR over the low-lying coastal areas shown in Figure 1 for Asia indicates the scale of the inundation and erosion problem. The situation in other coastal areas is similar to the one shown for Asia.

A key consequence of sea-level rise is the loss or degradation of wetlands in the coastal zone. There are, however, two compensating processes that might offset this potential threat: (1) an LSLR would inundate and flood areas that are now dry land, and thus, create new wetlands; (2) wetlands can grow vertically by accumulating sediment and organic material. The potential of these processes to slow down or prevent a major loss of wetlands as a consequence of LSLR may be limited due to two factors: (1) in many cases, land just inland of wetlands has been developed, and moving people and infrastructure to make room for the creation of new wetlands may not be acceptable socially and economically; (2) the rate of 21st LSLR could exceed the rates experienced during the last four to six thousand years, and while wetland ecosystems may have been able to keep pace with the past rise, they may not be capable of coping with a much accelerated rise.

In order to understand the potential impact of LSLR and the associated changes in the compartments of the coastal zone on ecosystems and their services, we need to characterize the different compartments, identify their services, and assess their resilience to spatio-temporal variations in these compartments. The coastal zone is an incredibly complex and diverse environment, which defies easy organization into neat compartments. Even a clear definition of the coastal zone is not available. Coastal ecosystems display a wide range of geological features, dynamic conditions, climate conditions, and species. Nevertheless, for an understanding of the vulnerability of coastal ecosystems to LSLR and inundation changes, as well as, their susceptibility to human activities to protect the coasts and reduce the impact of flooding, a classification is required. Here we will focus on those coastal and marine compartments most sensitive to changes in LSL.

For the marine environment, we follow Madden and Goodin (2007), who identify five main regions from the supratidal zone on the landward endpoint to the central ocean: the estuarine, freshwater-influenced marine, nearshore marine, neritic, and oceanic regimes (see Table 2 in Section 4.14.4). In addition, we also need to consider the land above the supratidal zone, which may be inundated, converted into wetlands, and eroded due to LSLR, depending on the current topography, the energy environment, and the geology.

In the following, we will first clarify our risk-based approach to the mitigation of impacts of LSL changes on coastal flooding and ecosystems. We will then discuss plausible changes in LSL and GSL and provide a typology of the sea-level hazards in the coastal zone including coastal protection (see Section 4.14.3). In Section 4.14.4, we will review the coastal ecosystems with emphasis on their service functions, and in Section 4.14.5 discuss the vulnerability of these systems to LSLR and coastal protection. Section 4.14.6 summarizes the sea-level related risk for coastal ecosystems, and in Section 4.14.7, we will discuss strategies and policies that might limit future loss of coastal wetlands.

4.14.2 A Risk-Based Approach to Mitigation and Adaptation

Changes in mean LSL and short-term temporal variations (such as waves, tides, storm surges) of LSL can significantly change the energy environment of a coastal area and lead to coastal erosion and inundation. Inland hazards caused by LSL rise include inundation, saltwater intrusion, increased erosion, and higher storm surges. As a result of LSL rise, the Probability Density Function (PDF) of these sea-level related hazards can change significantly. Any risk-based planning of mitigation and adaptation has to account for this.

Any decision on mitigation and adaptation needs to take into account the probability of the hazard actually occurring, and the ability of a system, be it a human socio economic system or an ecosystem, to cope with the hazard. The study of the vulnerability of human and natural systems to hazards is a relatively new interdisciplinary field, which is developing particularly with a view on climate effects, and other natural hazards. A common language has not been developed yet and experts from different field put different meanings to the terms used (e.g., Dolan and Walker 2003). In particular, approaches differ between natural and social sciences (e.g., Brooks 2003).

Here we take a risk-based approach that is commonly used for natural hazards and particularly geohazards. For a given hazard h, a given recurrence time interval T, and for a prescribed intensity I, the associated risk $r(I)$ expressed in currency is given by

$$r_h^T(I,x,t) = p_h^T(I,t)\cdot V_h^{a(x,t)}(I,t)\cdot a(x,t) \qquad [1]$$

where x is the location, t time, p the hazard giving the probability that the hazard with intensity I will occur in the considered recurrence interval, V the vulnerability of an asset a for hazard h at intensity I, and a being the asset exposed at location x. To assess the total risk R associated with a hazard, we can use

$$R_h^T(x,t) = \int_0^{I_{\max}} r_h^T(I,x,t)\mathrm{d}i. \qquad [2]$$

Equations [1] and [2] provide a basis for risk management and the prioritizing of mitigation, adaptation, and monitoring. The risk is strongly dependent on the chosen recurrence time interval. Selecting a short time interval may seriously underestimate the risk, while a very long interval may lead to unrealistically high risks.

Assets can be any system from a single building, a transportation infrastructure, a city, a socio economic system, to an ecosystem or a natural resource such as groundwater. We use the term vulnerability to indicate the damage a hazard would cause to an asset, if the asset was exposed to the hazard. This is the approach taken mostly in disaster risk research for natural hazards. Climate scientists tend to consider vulnerability in terms of the likelihood of impacts of weather and climate related events (Nicholls et al. 1999) or the damage inflicted by changes in climate statistics (outcome vulnerability (e.g., Kelly and Adger 2000; Pielke Sr. et al. 2012)), while social scientists often consider vulnerability as the set of socio economic factors determining the ability of a social system to cope with stress or change (contextual vulnerability) (Allen 2003). In our definition, vulnerability does not depend of the hazard actually occurring, but is a latent characteristic of the asset. For example, one building may be more vulnerable to fire hazards than another building, independent of the fire actually occurring.

All three factors in eqn [1] depend on time. Both natural and anthropogenic assets at a given location can change and their value can change as well. Vulnerability of the assets also can change over time. In particular, adaptation can reduce vulnerability, while pre-stress can increase it. If we denote the impact of adaptation at time t on vulnerability by $\alpha(t)$, then vulnerability is given by

$$V_h^{a(x,t)}(I,t) = V_h^{a(x,t)}(I,t)\Big|_{t=t_0} - \int_{t_0}^{t} \alpha(t)\mathrm{d}t. \qquad [3]$$

The probability p of a hazard h of intensity I occurring within time interval T also depends on time. Particularly for climate-related hazards, climate change will change p.

For most natural hazards, including most sea-level related hazards, there are limited options to impact p. However, in some cases, land use can significantly change the PDF of a hazard (e.g., for floods, droughts, landslides). Likewise, climate (in particular changes in precipitation and temperature) can modify the PDF significantly. Examples are the increasing melting of permafrost in northern Canada and Alaska, which has led to increased landslides that threaten roads and pipelines. Increased precipitation and periods of more rapid snow melt can change the PDF for floods and droughts (e.g., Solomon et al. 2007), and, importantly, changing intensity, frequency, and path of storms impact the PDFs for storm surges with potentially large spatial variability (e.g., Katsman et al. 2011; Schwerzmann and Mehlorn 2009).

The main measures for risk reductions lie in a reduction of vulnerability and, if possible, the spatial exposure of assets. For coastal ecosystems, mitigation through changes in exposure is of limited value, since coastal ecosystems are adapted to locations and often cannot be relocated. Thus, coastal protection is often the only means to reduce the impact of LSL changes on coastal ecosystems. However, coastal protections also modify many compartments of the coastal zone and thus can have a degrading impact on coastal ecosystems, or even remove the basis for existing ecosystems. It is this trade-off between protection and negative impacts that poses a great challenge to coastal zone management.

Adaptation and mitigation are insurance against the risk. While eqns [1] and [2] provide a basis for a quantitative analysis of the risk, willingness to engage in adaptation and mitigation depends on risk perception. Zahran et al. (2008) studied why cities would voluntarily commit to the Cities for Climate Protection (CCP) campaign and found that those cities that had suffered more from extreme events were more willing to commit. The challenge of LSLR is that it is a slowly developing disaster. We normally do not realize the hazard until it is too late. While there is a growing acceptance of the risk for coastal cities associated with LSLR, the risk for ecosystems, for which the societal value is not obvious, is much less accepted, and costs for adaptation and mitigation are often postponed.

Another term relevant for our discussion is resilience. Resilience can be defined as the ability of a system to absorb disturbance while retaining its basic function and structure (Walker and Salt 2006). Social and ecological resilience are related (Adger 2000). For a social system, resilience is the ability to cope with external and internal stresses as a result of social, political, and environmental change. For an ecological system, resilience is a characteristic of the ecosystems to maintain itself in the face of disturbance. Particularly, for social communities depending on ecological and environmental resources for their livelihoods, there is a clear link between social and ecological resilience. On a global scale, resilience of humanity is linked to the resilience of the global biosphere to human interference, including human climate forcing (National Research Council 2005) coupled with natural climate variations, which are often quite large (Rial et al. 2004; Meko et al. 2007). There are global boundaries the transgression of which may put the global ecosystem into a new state, which could still be acceptable for the ecosystems, but outside of the safe space for humanity (Rockström et al. 2009a,b). Decisions on mitigation of impacts on ecosystems have to account for this link between ecological and social resilience.

4.14.3 The Hazards: Sea-Level Change and Coastal Protections

We define LSL as the height h of the sea surface above the underlying surface of the solid Earth, e.g.,

$$h(\lambda,\theta,t) = \begin{cases} r_1(\lambda,\theta,t) - r_0(\lambda,\theta,t) & : \text{ in the ocean} \\ 0 & : \text{ on land,} \end{cases} \qquad [4]$$

where r_0 and r_1 are the geocentric positions of the sea floor and sea surface, respectively (Plag 2006a). λ and θ are the geographical longitude and latitude, respectively. Variations $\xi(t) = h(t) - h_0$ of LSL are the result of variations in r_0 or r_1 or both. GSL is the average taken over the surface of the oceans. Changes in GSL equal the changes in the Global Ocean Volume (GOV). We note here that in many publications, the term 'sea-level' is not explicitly defined, and often refers to sea surface height observed in a geocentric reference frame (also sometimes falsely referred to as absolute sea-level, Blewitt et al. 2010). LSL defined by eqn [4] often is referred to as relative sea-level, although the distance between sea surface and land surface is an absolute quantity independent of the reference frame.

LSL as defined above is the quantity that is directly related to the potential impact of global and regional changes in climate and sea-level in a given coastal area. At any location, LSL is the result of a number of global, regional, and local-scale Earth system processes altering sea surface height, land surface height, or both (Figure 2). These processes, which act on a wide range of time scales, from a few seconds to millions of years, include mass relocation in ice sheets, glaciers, land water storage, and oceans; deformation of the solid Earth and gravity field changes caused by the mass relocation; changes in ocean heat storage and ocean currents; changes in atmospheric circulation; tectonic processes; and local coastal subsidence caused by natural and anthropogenic processes. These processes lead to large spatial variation in LSL on all time scales, and the relation between changes in GSL and LSL at any given coastal location is rather complex. For example, melting of ice on Greenland would increase GSL, but it would lead to a fall of LSL at the coasts of Greenland and any land mass in the vicinity of Greenland, while the rise in LSL on the Southern hemisphere would be larger than the global average.

No single Earth system model is currently available that can accurately predict past, present, or future LSL changes, and it is unlikely that such a model will become available in the near future. Moreover, underlying processes (including future greenhouse gas and aerosol emissions and land use change Lovejoy and Schertzer (2012); effects on climate of anthropogenic re-engineering of the planet (Syvitski 2012); changes of ice sheets and glaciers; natural low-frequency climate variations National Research Council (2005)) likely will remain unpredictable on century time scales for a long time to come (McMichael et al. 2006; Lipscomb et al. 2009). Thus, quantitative, model-based predictions for twenty-first century LSL with sufficiently narrow uncertainties to be actionable cannot be provided today, and most likely not in the foreseeable future.

Our inability to predict future LSL trajectories within narrow uncertainty bands rules out a deterministic approach to coastal risk assessments and the planning of coastal protection as

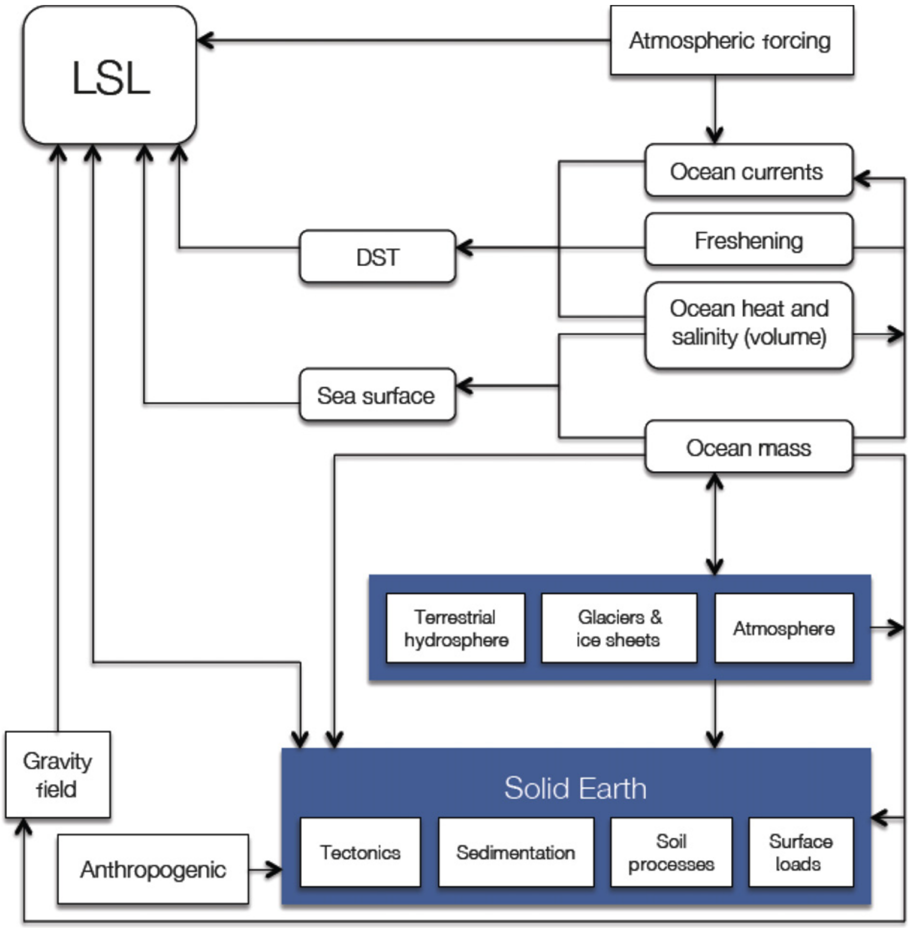

Figure 2 Processes and factors causing long-period LSL changes. Mass movements in the terrestrial hydrosphere (groundwater, rivers, lakes, and reservoirs) and land-based cryosphere (glaciers and ice sheets) and mass exchange with the ocean load and deform the solid Earth and affect the gravity field. The deformations and the associated gravitational changes result in LSL changes, depending on where mass has been relocated. Ocean mass changes as well as ocean volume changes caused by heat and salinity changes affect the sea surface position. Heat and salinity changes also affect the ocean currents and thus change the Dynamic Sea Surface Topography (DST). Freshening caused by melting sea ice contributes to both changes in GOV and DST. Atmospheric circulation forces regional wind-driven currents affecting the DST. DST and sea surface changes caused by regional and global processes change LSL in any location. The atmosphere also acts locally on the sea surface and thus changes sea level. Past changes in the ice sheets and glaciers lead to postglacial rebound, which affects sea level through vertical land motion and geoid changes. Tectonic processes in the solid Earth both result in vertical land motion, changes in the size of the ocean basins, and changes in the geoid. In areas where sedimentation takes place, the compaction of the sediments and their load on the solid Earth introduce vertical land motion. Moreover, changes in LSL feedback on the solid Earth and can cause the destruction of peat through oxidation and thus lead to subsidence. Anthropogenic vertical land motion associated with exploitation of groundwater, oil, and gas as well as changes in sedimentation can change the Earth surface position. Variations in sedimentation due to river regulation (reduction) or land use (increase) also affect LSL, particularly near river deltas. Figure modified from Plag, H.-P., 2006a: Recent relative sea-level trends: an attempt to quantify the forcing factors. *Phil. Trans. Roy. Soc. London, A*, **364,** 1841–1869 and Sahagian, D., et al., 2009: Earth observation: serving the needs of an increasingly global society. *Global Geodetic Observing System: Meeting the Requirements of a Global Society on a Changing Planet in 2020,* H.-P. Plag and M. Pearlman, Eds., Springer Verlag, Berlin, 153–196.

a basis for mitigation of inundation risks. Instead, a statistical approach is needed that takes into account the PDF of decadal to century-scale LSLR. In order to avoid under or over investments, this approach requires a reliable estimate of the PDF of LSLR. In particular, the reliability of the PDF at the high end, e.g., the large rapid rises, is crucial. For sea-level hazards, a rapid large rise is the improbable, high-impact event that is difficult to plan for. It is this event that will cause huge disasters if not anticipated and planned for, and the event that will demand extreme economic efforts to prepare for, which could be wasted if the probability of the event is overestimated.

4.14.3.1 GSLR Discussion: The Deterministic Approach

Much of the discussion on ocean-warming and ice-melt induced sea-level rise has focused on projected GSLR for the twenty-first century. A related question raised in many contributions is to what extent the observed twentieth century GSLR of $\approx 0.2\ \mathrm{mm\ year}^{-1}$ already showed an accelerated rise compared to a presumably far more stable GSL during the last few millenniums (Figure 3, see also Church and White (2006)). Cronin (2011) points out that the notion of a very stable sea-level over the last two millenniums is not supported by

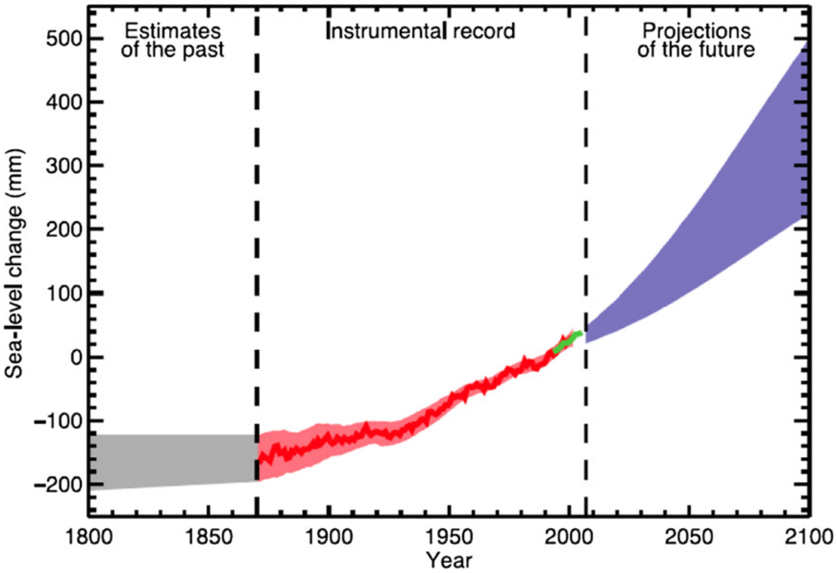

Figure 3 GSL changes between 1800 and 2100. GSLR prior to about 1850 is generally estimated to be on the order of 0 to 2 mm year^{-1}. Since 1850, the rate of GLSR has been on the order of 2 mm year^{-1} with a possibility of larger rates of about 3 mm year^{-1} at the end of the last century (e.g., Cazenave et al. 2010). IPCC projected rates of GSLR for the twenty-first century are between 3 and 5 mm year^{-1}, depending on assumptions of the emission scenario (Bindoff et al. 2007). However, as noted in the text, the models used for these projections do not accurately include all human climate forcings nor are they able to represent low-frequency climate variability and longer-term changes in climate statistics. If, for example, the large ice sheets contribute significantly, then the rates would be much higher. Consequently, the range of plausible GSL trajectories for the twenty-first century is much wider than the figure indicates. Figure from Bindoff, N. L., et al., 2007: Observations: oceanic climate change and sea level. *Climate Change 2007: The Physical Science Basis. Contribution of Working Group I to the Fourth Assessment Report of the Intergovernmental Panel on Climate Change*, S. Solomon, D. Qin, M. Manning, Z. Chen, M. Marquis, K. B. Averyt, M. Tignor, and H. L. Miller, Eds., Cambridge University Press, Cambridge, United Kingdom and New York, NY, USA.

observations, particularly if regional deviations from the global mean are taken into account. However, compared to the large fluctuations of GSL and even larger fluctuations of LSL in many locations, during the last million years, GSL has to be considered exceptionally stable over the last few thousand years (**Figure 4**).

Figure 5 summarizes the GSLR projections for the twenty-first century given in the IPCC assessments. The models used for the predictions have been validated against the recorded data from past decades, but the model simulations underestimate the GSLR observed during the twentieth century (see **Figure 5.21** in Bindoff et al. 2007). The large range of IPCC twenty-first century GSL trajectories arises from the range of the projected emission scenarios, as well as, uncertainties in the model response to these scenarios. However, since the models used for the projections do not accurately capture all human and natural climate forcings, the actual range of plausible GSL trajectories is much larger than indicated in **Figure 5**. It is interesting to note that in earlier studies, sea-level rise estimates for the twenty-first century were larger than those predicted by IPCC AR4 (see, e.g., Figures 1–4 in Titus 1988).

Concerning thermal expansion, model simulations of twentieth century heat uptake by the oceans do not fully match the model predictions (Cazenave et al. 2009, 2010), thus putting a question mark on the validity of the projections for this contribution. Observations of the retreat of glaciers and ice caps exclusive of Greenland and Antarctica (GIC) have been, in a number of situations, more rapid than models have simulated (e.g., Meier et al. 2007). The uncertainty in the projections of surface climate, where glaciers and ice sheets exist, adds to the uncertainty of the modeling of GIC response to temperature and environmental changes.

Most importantly, uncertainties related to the potential contribution of the Greenland Ice Sheet (GIS) and Antarctic Ice Sheet (AIS) make it very difficult to constrain the upper limit of the 21st GSLR. Particularly, the AR4 emphasizes the large uncertainty in the upper limit arising from an unknown potential contribution of the large ice sheets. This has lead to a significant debate within the scientific community about the quality of the IPCC GSLR projections for the twenty-first century. A strong focus has been on the potential contribution of the large ice sheets due to potential dynamic processes that may occur if the ice sheets warm (e.g., Pfeffer et al. 2008; Holland et al. 2008; Bamber et al. 2009; Jiang et al. 2010). Potential dynamic effects include very rapid movements of ice streams, leading to potential GSLR exceeding 10 mm year^{-1}, a contribution far larger than any of the other terms. The possibility of a collapse of parts of the ice sheets cannot be excluded (e.g., Vaughan et al. 2007), especially if there would be rapid loss of surrounding ice shelves that could increase the ice stream flows (e.g., Rignot et al. 2008a). The physics of these processes are not well understood and, hence, these processes are not accounted for in the models. However, omitting what likely will be the most important contributor to GSLR must raise a red flag: the IPCC projections of 21st GSLR and beyond may be significantly too low. It is important to emphasize, however, that since our understanding of the climate system is incomplete; other changes in global sea-level rise (including a leveling off or even a fall) are certainly possible. This could

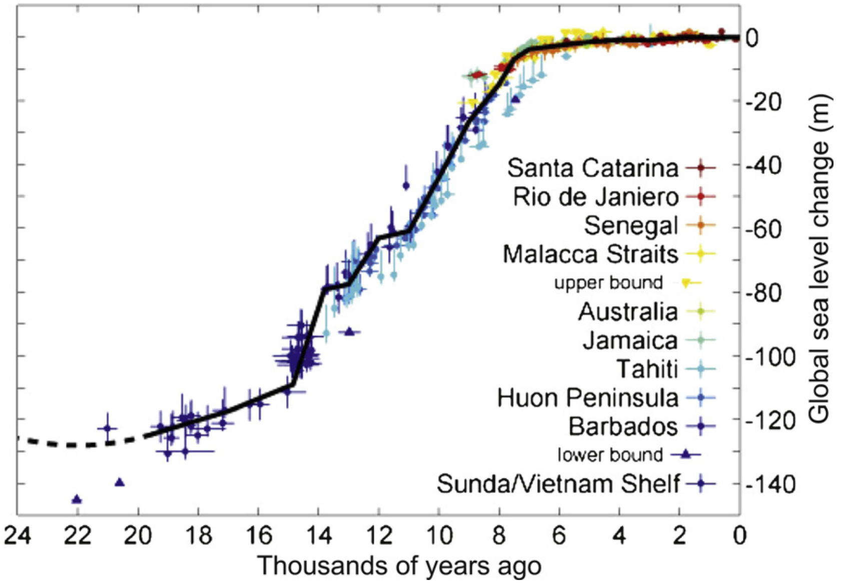

Figure 4 GSL during the last 24 000 years. Data from Fleming, K., P. Johnston, D. Zwartz, Y. Yokoyama, K. Lambeck, and J. Chappell, 1998: Refining the eustatic sea-level curve since the last glacial maximum using far- and intermediate-field sites, *Earth Planet Sci. Lett.* **163** (1–4), 327–342, http://dx.doi.org/10.1016/S0012–821X(98)00198–8; Fleming, K. M., 2000: Glacial rebound and sea-level change constraints on the Greenland ice sheet, Ph.D. thesis, Australian National University; Milne, G. A., A. J. Long, and S. E. Bassett, 2005: Modelling holocene relative sea-level observations from the Caribbean and South America. *Quat. Sci. Rev.*, **24** (10–11), 1183–1202, http://dx.doi.org/10.1016/j.quascirev.2004.10.005. Modified from the figure available at http://en.wikipedia.org/wiki/File:Post-Glacial_Sea_Level.png.

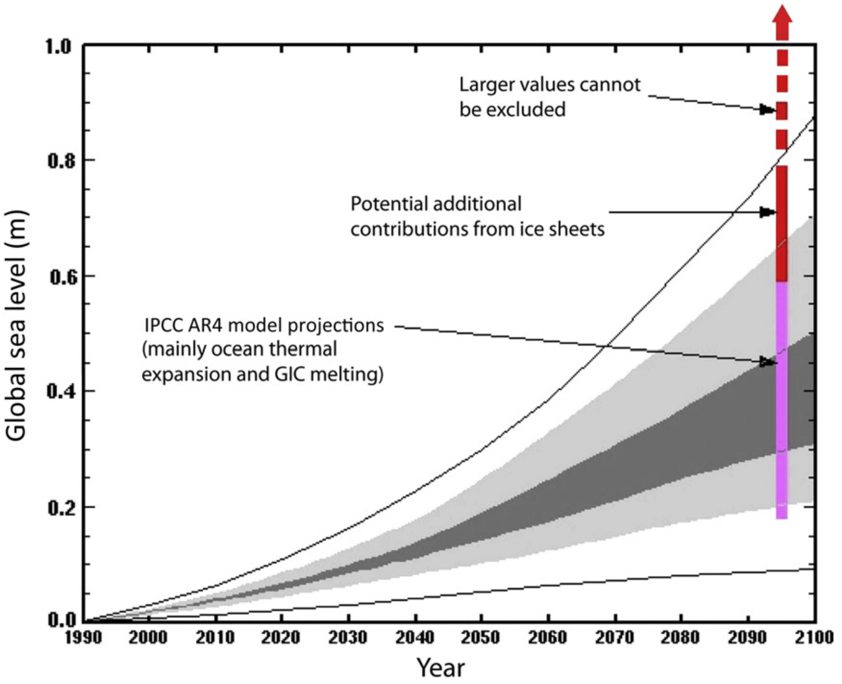

Figure 5 Summary of projected GSLR for the twenty-first century: The lines and shading indicate the IPCC 2001 projections for the period 1990–2100 (Church et al. 2001), with the central dark shading being an average of models for the range of SRES greenhouse gas emission scenarios. The light shading is the range for all models and all SRES scenarios and the outer bold lines include an allowance for land-ice uncertainty. The vertical bars at 2095 indicate the spread of the updated AR4 IPCC projections for the SRES scenarios (Meehl et al. 2007): the magenta (lighter) bar indicates the range of model projections, mainly accounting for ocean thermal expansion and melting of GIC. The red bar is a potential additional contribution from a dynamic effect of the GIS and AIS. Note that the IPCC AR4 states that "larger values cannot be excluded, but understanding of these effects is too limited to assess their likelihood or provide a best estimate or an upper bound for sea-level rise." Modified from Church, J., et al., 2010: Sea-level rise and variability: synthesis and outlook for the future, in understanding sea-level rise and variability. *Understanding Sea-Level Rise and Variability.* J. Church, P. L. Woodworth, T. Aarup, and S. Wilson, Eds., Wiley-Blackwell, 402–419, ISBN: 978-1-443-3451-7.

occur, for example, from multiple large volcanic eruptions, which could significantly reduce ocean heat content. There is also an inadequate understanding of long-term variations in solar forcing and of low-frequency natural variations in climate system heating and cooling.

The focus on deterministic model predictions, which are the basis of most of the recent climate change assessment and impact studies (even those based on quasi-statistical approaches such as ensemble studies), however, are hampering our ability to assess the true probabilities of climate change (Dessai et al. 2009). As a consequence, the risk associated with future sea-level hazards may be underestimated, eventually misguiding adaptation. As emphasized by McMichael et al. (2006), modeling cannot be an exact science, as the models themselves are hypotheses. As just one incompletely understood issue, there is considerable uncertainty about the future trajectories for greenhouse gas emission, e.g., one of the key human climate forcings, which together with residual uncertainties about the sensitivity of the climate system to these trajectories produces a wide range of plausible trajectories for GT and regional temperatures. As the human climate forcing continues, the probability of exceeding critical thresholds and causing rapid changes in climate and environment should be expected to also increase (Harrison and Stainforth 2009).

If we cannot skillfully predict sea-level changes in the coming decades, what would be a more prudent approach? An assessment of risks from any plausible change in sea-level can provide guidance (Donner 2012). For this approach, considering the statistical characteristics of past behavior of the Earth system is a starting point. Compared to the large fluctuation in GT and GSL over the last million years and more, the Earth system has been in a mediocre state over the last few thousand years with very small changes. In 'Mediocristan,' single extremes do not matter; it is the integral over the gradual changes that count (Taleb 2010). However, human climate forcing and long-term climate variability could push the Earth system into a state where extremes are more common and much larger. In 'Extremistan,' single events are crucial. For example, a rapid melting of a large portion of the GIS or AIS would constitute such an extreme event. Similarly, a significant change of ocean circulation could catapult the Earth system into a different state with severe consequences for ecosystems and humanity.

While we are used to our socio economic system being in Extremistan, with the Great Depression, the First and Second World Wars, and the Internet being examples of extreme events that determined the future, we do not have this view on the development of the Earth system. In our planning, we basically rule out that extreme events can have a determining impact. Climate modeling is based on the assumption that the planet is in Mediocristan. The multi-decadal climate models have demonstrated no skill at predicting extreme events leading to a change in the state of the system. The models are not able to model past extreme events. For a system that has the potential to be in Extremistan, these models are almost useless as a basis to determine the PDFs of hazards. For a system in Extremistan, so-called 'Black Swan' events have a larger impact on the system's future than the gradual changes. Black Swan events are improbable, high-impact events that (1) are outside our experience; (2) have an extreme impact; (3) can be explained after the fact Taleb (2010). Considering the dependence of our civilization on the coastal zone and coastal ecosystems (Edwards 2008) and the fact that we are still migrating into the coastal zone, a sea-level Black Swan, that is a rapid rise exceeding all expectations, would be truly disastrous. Coastal ecosystems have the ability to adapt to slow changes in mean sea-level through migration, but for most systems, there will be a threshold for the speed of changes with the systems not being able to adapt to changes at a pace above the threshold.

There is a chance that the current scientific discussion of GSLR is preparing the ground for a 'Black Swan' event. Recent assessments of GSLR in the twenty-first century have been based on models calibrated to the recent past (**Figure 3**). These models, however, are incapable of predicting the rapid sea-level rise events that have taken place many times over the last one million years, with changes during one century exceeding present-day rates by a factor of 50 and more. The discussion of the upper limit for the twenty-first century is also based on the recent past and assumptions, excluding the rapid rises that are documented in the paleo-records. This bias to low estimates and low upper bounds creates a mindset that is no longer open for the improbable, high-impact event, e.g., the Black Swan. Another reason why the last few thousand years with relatively stable condition may not be a good basis for assessing the future, is the fact that, humanity over the last few hundred years has re-engineered the Earth system, with the most dramatic changes during the last decades, as human population continues to grow and increasingly alters the environment (Syvitski 2012, e.g.,). A more comprehensive look at the statistical properties of the Earth system in terms of century-scale GT, GSL, and LSL changes is needed.

4.14.3.2 Probability Density Function of GSLR

In order to assess the character of the sea-level rise Black Swan, we need to consider the PDFs of century-scale changes in relevant parameters and relate these to plausible changes in these parameters for the twenty-first century. There are many relevant parameters, but we will consider here only two examples, namely century-scale GSLR and Global Temperature Rise (GTR) (denoted here as GSLR_{100} and GTR_{100}, respectively). Considering that over the last 50 years, the world ocean accounts for 90% of the global warming (Levitus et al. 2012), we have to acknowledge that GTR is a poor indicator of GSLR, but many discussions focus on GTR. For example, ocean heating and continental glacier changes cannot be directly related to the GTR. Ocean heating measured in Joules depends on the process in which heat is transferred to the ocean, and only weather patterns (temperature, precipitation, cloud cover) and other environmental changes in the ice-covered region matter in terms of melting and runoff into the sea.

There is very little information available to determine the location-dependent PDF of LSL rise for many locations. For GSL, information on changes over the last 400 000 to 800 000 years is available from studies of several proxies (see, e.g., Hansen et al. 2008; for an overview). In the following, we have used observed Antarctic temperature (Vimeux et al. 2002) as a proxy for GT to determine time series of GTR_{100} (**Figure 6**) for the last 425 000. The comparison of the observed Antarctic

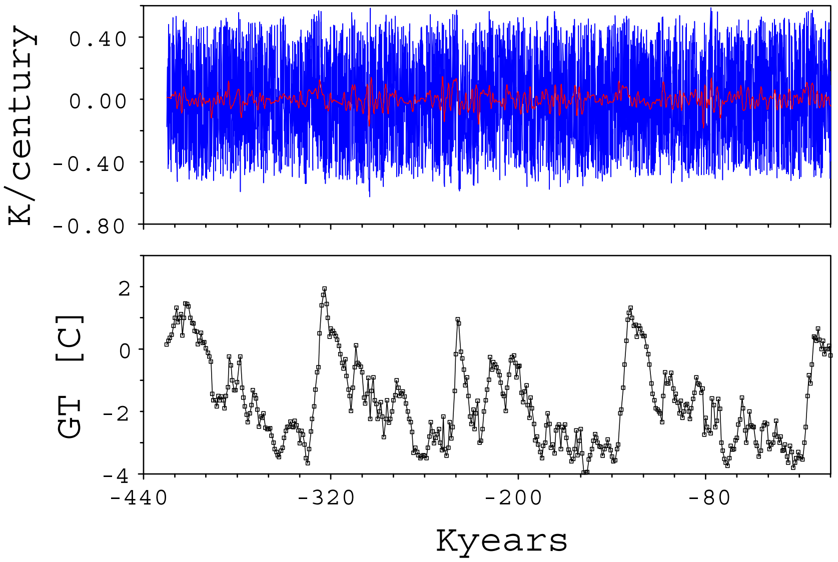

Figure 6 GT and GTR_{100} over the last 425 000 years. Lower diagram: observations of Antarctic temperature changes (Vimeux et al. 2002), which compare well to the GTR modeled by Hansen et al. (2008). Upper diagram: GTR_{100}; the red curve is the GTR_{100} determined from a spline interpolation of the lower curve; the blue line has a random fluctuation of the GTR_{100} around the GTR_{1000} of ±0.4 K/century. See text for details.

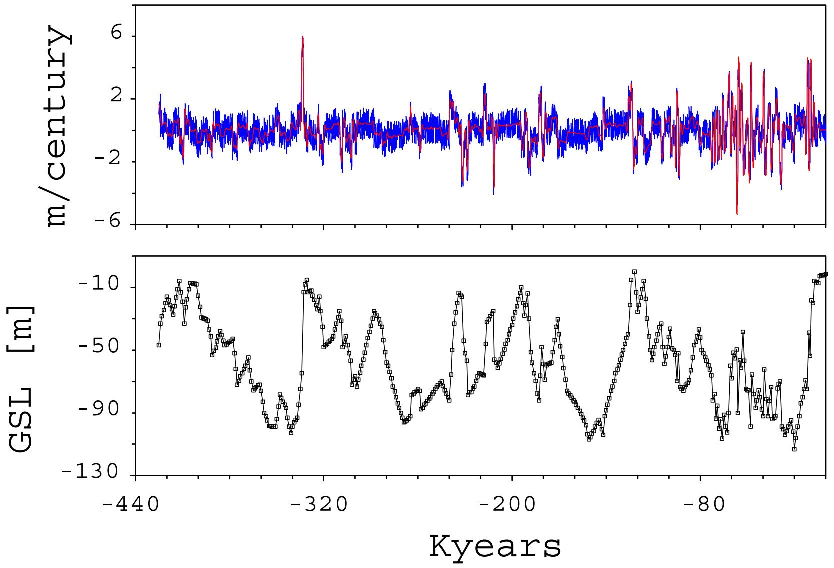

Figure 7 GSL and $GSLR_{100}$ over the last 425 000 years. Lower diagram: GSL determined from Red Sea sediments Siddall et al. (2003). Upper diagram: $GSLR_{100}$; the red curve is the $GSLR_{100}$ determined from a spline interpolation of the GSL curve; the blue line has a random fluctuation of the $GSLR_{100}$ around the $GSLR_{1000}$ of ±1 m/century. See text for details.

temperature to model GT (Hansen et al. 2008) show that the fluctuations of the Antarctic data is larger than the modeled GT, thus leading to a slightly more variable GTR_{100}. For the GSL, we use data provided by Siddall et al. (2003) to determine a time series of $GSLR_{100}$ (Figure 7). We then use these time series of GTR_{100} and $GSLR_{100}$ to determine the PDFs of GTR_{100} and $GSLR_{100}$ (Figure 8).

For most of the period considered, the data available for GT and GSL has a temporal resolution of 1000 years or less. In the first step, we use a spline interpolation of the data to determine the century changes. However, the spline interpolation very likely is too smooth, thus resulting in a PDF far too narrow. Particularly the temperature data lead to a very narrow PDF confined to the interval between ±0.25 K per century. In order to get a better assessment of the century-scale rates, we have to make assumptions with respect to the deviation of these rates from the millennium averages. For GT, we assume that GTR_{100} fluctuates randomly around the millennium average with ±0.4 K. The random fluctuation drastically changes the PDF, and it appears that the assumed amplitude of 0.4 K per century is at the upper limit of what is consistent with the available data.

For sea-level, the values for $GSLR_{100}$ determined from a spline interpolation of millennium rates cover the interval between -5 m per century and $+7$ m per century, with larger positive rates (rise) being more likely than larger negative rates. For GSLR, we also test the effect of adding a random fluctuation of $GSLR_{100}$ around $GSLR_{1000}$ and assume a fluctuation of ± 1 m. For GSL, adding a random fluctuation with this amplitude does not significantly change the PDF.

Comparing the twentieth century change in global temperature of (0.74 ± 0.18) K (Meehl et al. 2007) to the PDF for GTR_{100}, it is clear that this rise falls outside the PDF for the last 425 000 years. More drastically, the IPCC AR4 predictions for several emission scenarios are far outside the range of GTR_{100} documented in the paleo-data. There are two alternative interpretations: (1) the predictions are inaccurate, and by far, overestimate of the GTR_{100} for the twenty-first century possible in the Earth system or (2) the predictions are realistic, in which case the Earth history of the last 450 000 years provides no useful analog for the impact of the predicted GTR_{100} for the twenty-first century. In particular, if alternative (2) were correct, many ecosystems would not be able to cope with the unparalleled speed of GTR_{100}. For coastal ecosystems, any such rapid change would lead to double stress from changes in the region's weather patterns and from rising sea-levels.

Do we have indications which of the two alternatives are more likely? The fact that many of the characteristic parameters of the Earth system (including atmospheric constituents such as CO_2N_2O, and CH_4, damming of rivers, water use, nitrogen deposition, ozone deletion, urban population, ocean ecosystems, coastal zone structures, ocean zone biogeochemistry, loss of tropical rain forests and woodlands, and global diversity; see e.g., Steffen et al. (2004) and **Figure 1** in Syvitski (2012)) have already attained values outside their range of variability during the last one million years or more seems to support alternative 2. It is interesting to note that, for example, the CO_2 concentration of 385 ppm observed in 2008 exceeds the previously occurring maximum of 300 ppm observed during the last 800 000 years by 65% of the total Glacial-Interglacial Range (GIR) of 130 ppm during this time (Karl et al. 2009). The speed of change in many Earth system parameters is also unparalleled. For example, while during the last million years, maximum changes in CO_2 on the order of 100 ppm took place over thousands of years, humanity accomplished this in less than three centuries. Under these unparalleled conditions, the response of the climate system to the combined changes in the Earth system may also exceed all rapid responses documented in the paleo-records. However, this does not exclude alternative 1.

The twentieth century $GSLR_{100}$ of (0.2 ± 0.1) m per century falls well into the PDF for $GSLR_{100}$ (**Figure 8**). Similarly, the IPCC AR4 prediction for twenty-first century thermal expansion and for combined GSLR due to thermal expansion, ice sheet, glaciers, and land water storage contributions are within the more or less central domain of the PDF. However, considering that the predicted GTR_{100} is far outside any past experience, there are unresolved questions as to their value to assess the risks associated with GSLR and LSLR in the coming decades.

Is there a relation between GTR_{100} and $GSLR_{100}$? Using the data determined from the spline-interpolated curves, we find no correlation between GTR_{100} and $GSLR_{100}$. One reason for this lack of correlation could be large errors in the timing of the rapid changes in GT and GSL. The proxies used to determine these curves have significant uncertainties in time. Another reason could be the complex nature of the Earth climate systems, where GSL changes do not lead to correlated GSL changes. If, for example, an increase in GSL leads to changes in ocean circulation with impacts on the latitudinal temperature and precipitation distribution, then an increase in GT could lead to increasing ice sheets and a fall in GSL. The high correlation between IPCC AR4 predicted 21st GTR and GSLR is an indication of the models not reflecting the complexity of the climate system.

How much does the location-dependent $LSLR_{100}$ deviate from $GSLR_{100}$? The answer to this question helps to assess the probability of large rises along parts of the coasts. In the following, we will first review the science basics of LSL changes and analyze the relevant processes. This will provide the basis to assess both the range of plausible changes and the spatial variability.

4.14.3.3 The Cumulative LSL Equation

As mentioned above, Earth system models available today are not capable of modeling all LSL forcing processes and predicting LSL changes. However, the scientific understanding of the link between individual global, regional, and local processes and LSL changes is well developed. Therefore, a local approach can be used to describe the relation between forcing processes and LSL. For our purpose, it is helpful to separate the equation describing LSL as a function of the various forcing processes into a high-frequency and a low-frequency part (Plag 2006a). For the assessment of impacts, the combined effects of the high-frequency and low-frequency part of the LSL equation are important.

LSL variations ξ can be written as:

$$\begin{aligned}\xi(\vec{x},t) &= W(\vec{x},t) + T(\vec{x},t) + A(\vec{x},t) + S(\vec{x},t)\\ &\quad + C(\vec{x},t) + F(\vec{x},t) + I(\vec{x},t) + G(\vec{x},t)\\ &\quad + L(\vec{x},t) + P(\vec{x})(t) + V(\vec{x},t),\end{aligned} \qquad [5]$$

where t is time, t_0 an arbitrary time origin, and ξ is given relative to an arbitrary zero level (modified from Plag (2006a)). Here we include the processes W: waves, T: tides, A: LSL changes caused by atmospheric forcing, S: steric changes, C: ocean circulation, F: freshening due to melting of sea and land ice, I: mass changes in the large ice sheets, G: mass changes in the continental glaciers and ice caps, L: land water storage changes, P: postglacial rebound, V: vertical land motion other than postglacial rebound or land motion caused by other surface loading. Some of these processes lead to predominately short-period variations (e.g., waves), while others are pre-dominantly long-period to secular in nature (e.g., postglacial rebound caused by the melting of the ice sheets of the last ice ages). Most terms have both short and long-period variations, although with different significance (**Table 1**).

Equation [5] illustrates the complex nature of LSL variations as the result of processes in the global water and energy cycles merged with geodynamic processes and, recently, anthropogenic activities. The processes separate into two large groups, namely those that are mainly volume changes of the ocean

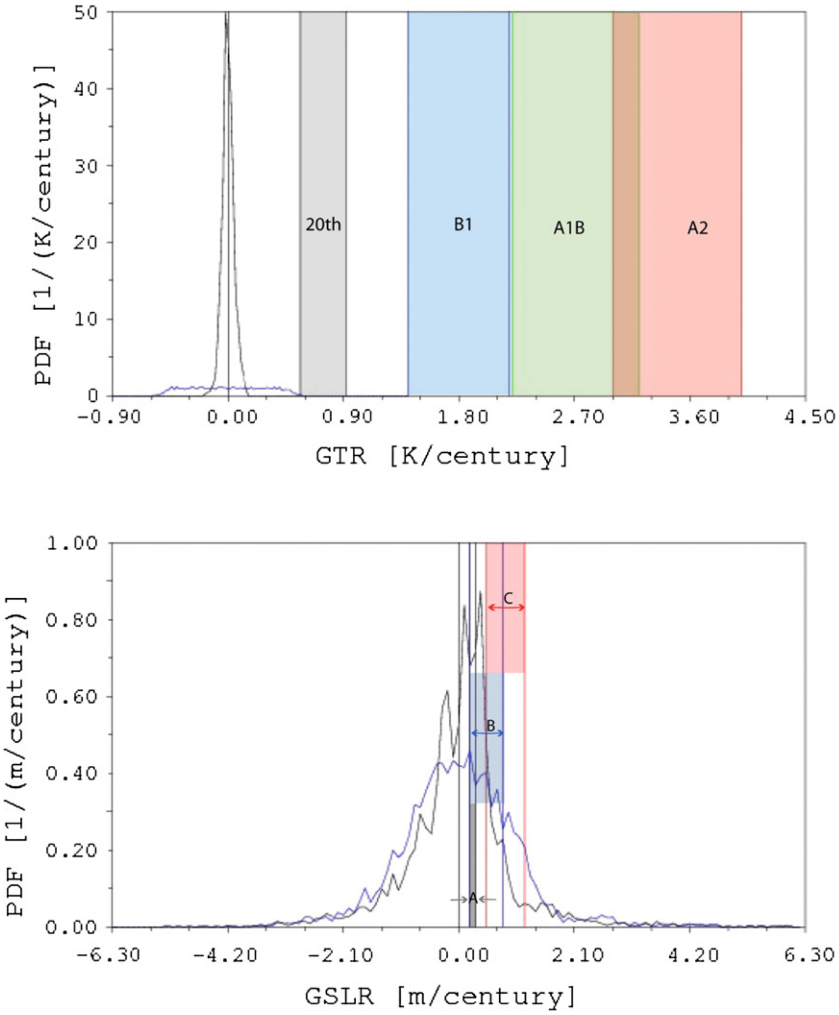

Figure 8 Probability density function of $GSLR_{100}$ and GTR_{100}. In each diagram, the black curve is the PDF based on the spline-interpolated millennium averages; and the blue curve the PDF determined from the rates including the random variation of the century rates around the millennium averages. The vertical lines indicate current rates and twenty-first century predictions. Left: PDF for GTR_{100}; A2, A1B, and B1 are the SRES emission scenarios used in IPCC AR4 (Meehl et al. 2007). Right: PDF for $GSLR_{100}$. A: twentieth century observed GSLR (Bindoff et al. 2007); B: predicted twenty-first century GSLR due to thermal expansion (Meehl et al. 2007); C: plausible twenty-first century GSLR including contributions from ice sheets, glaciers, and land water storage.

water (and thus affect GOV, but not GOM) and those that are associated with significant mass redistribution in the global water cycle (and thus may also affect). Before we address our ability to predict LSL variations on century time scales, we first provide the theoretical background for LSL changes caused by mass redistribution and describe the current knowledge in terms of current contributions and predictions for each of the processes included in eqn [5].

4.14.3.4 Mass-Induced LSL Variations

Processes involving redistribution of mass in the water cycle are all associated with viscoelastic–gravitational effects on LSL, leading to very distinct spatial and temporal patterns of LSL variations caused by these processes. In order to emphasize the importance of the fundamental relationship between any mass transport in the global water cycle and the LSL, we consider the case where the GIS mass increases and the AIS melts with the two changes being exactly in balance. This mass movement will not change the GOM or induce any GSL change, but LSL will fall significantly over large regions of the southern oceans and increase over large parts of the northern hemisphere. Thus, LSL changes caused by mass redistribution in the global water cycle depend crucially on where the mass redistribution takes place (as reconfirmed by Mitrovica et al. 2009).

The governing equation that links mass redistribution to LSL variations ξ (first introduced by Farrell and Clark 1976) can be written as:

$$\xi(\vartheta,\lambda,t) = c(t) + \int_{-\infty}^{t}\int_{0}^{\pi}\int_{0}^{2\pi} G(\vartheta,\lambda,\vartheta',\lambda',t-t') \qquad [6]$$

$$\frac{\mathrm{d}}{\mathrm{d}t'}\{O(\vartheta',\lambda',t')\rho_{\mathrm{W}}\xi(\vartheta',\lambda,t') + [1-O(\vartheta',\lambda',t')]\rho_{\mathrm{L}}\eta(\vartheta',\lambda,t')\}\sin\vartheta'\,\mathrm{d}\lambda'\,\mathrm{d}\vartheta'\,\mathrm{d}t',$$

Table 1 Processes contributing to LSL variations. Upper part: processes with significant short-period variations. Lower part: processes with negligible short-period variations

S.	*Process*	*Short-term*	*Long-term*	*Comment*
W	Waves	From seconds to more than 30 min (tsunamis)	Changes in wave energy due to climate	Relevant for coastal erosion
T	Tides	Monthly, fortnightly, diurnal, semi-diurnal, and shorter periods	Semi-annual, annual, and nodal tides	Changes due to climate are very small
A	Atmosphere	From seconds to months	Intraseasonal to secular; with multi-decadal variation in mean air pressure distribution and wind field changes impacting sea level	Can create multi-decadal trends on the order of several millimeters per year

S.	*Process*	*Long-term*	*Comment*
S	Steric	Most changes are on seasonal time scales, with multi-decadal to secular trends	Can contribute on the order of 50 cm per century
C	Circulation	Some interannual to multi-decadal variations; long-term changes in ocean circulation, including a significant slowing or an interruption of the thermohaline circulation	Long-term changes could have significant impacts on the DST and a feedback on regional climate
F	Freshening	Contributes to the seasonal cycle in sea level	A significant long-term reduction of sea ice would impact ocean salinity and GOV
I	Ice sheets	Contribute to the seasonal changes in Global Ocean Mass (GOM) as well as interannual to multi-decadal variations	The ice sheets are the main source for potentially large and rapid GSLR, with large spatial variations in LSLR (fall in the near-field and rise in the far-field).
G	Glaciers/ice caps	Contribute to seasonal changes in GOM; are a main contribution to present-day GSLR	Could contribute to increased GSLR; the spatial pattern in LSLR is complex due to the spatial distribution
L	Land water storage	Contributes to seasonal, interannual, and multi-decadal changes in GOM	Land use changes such as deforestation, irrigation, water reservoirs contribute to long-term changes in GOM; permafrost melting also may have an effect
P	Postglacial rebound	Produces significant secular land uplift in and around formerly glaciated areas and small subsidence in some far-field regions	
V	Vertical land motion	Earthquakes can lead to significant (order 1 m or more) sudden vertical displacement; tectonic processes and natural and anthropogenic subsidence can cause transient and secular vertical displacements of 250 mm year^{-1} and more	

Table 2 Regimes of the coastal zone

Regime	*Description*
Dry land	Land above the high water mark, which is rarely inundated by storm surges.
Littoral zone	The littoral zone extends from the high water mark to shoreline areas that are permanently submerged.
Estuarine	Estuarine regimes are enclosed or semi-enclosed coastal water bodies that are influenced by freshwater input that reduces salinity to below 3.0% during at least two months of the year. These waters are intimately linked with their watersheds, receiving nutrients, materials, and freshwater during a significant part of the year.
Freshwater influenced	Freshwater-influenced regimes are coastal waters that have no distinctly enclosing morphology, yet receive a significant amount of freshwater input from land during at least parts of the year. In such cases, an unenclosed marine water column may be influenced by freshwater in the form of an active river plume, an overlying freshwater lens or a groundwater seep discharge. They often may have surface characteristics of estuaries, but deeper waters may be completely marine.
Nearshore marine	Nearshore marine regimes are those coastal waters that are truly marine in character ($>$3.0% throughout the year) and not influenced by significant freshwater. The nearshore marine regime extends from the land margin to the 30 m depth contour.
Neritic	The neritic regime is the region of marine waters ($>$3.0% throughout the year) between the 30 m depth contour and the continental shelf break, which occurs at approximately at 200 m water depth.
Oceanic	The oceanic regime represents the marine realm beyond the continental shelf break, generally occurring at 150–300 m of water depth at the seaward edge of the continental shelf. These waters can range to several thousands of meters depth. The marine waters of the oceanic regime are sufficiently distant from land that they receive little or no influence of freshwater, nutrient and sediment inputs, except around large islands.

Modified from Madden, C. J., and K. L. Goodin, 2007: *Ecological Classification of Florida Bay Using the Coastal Marine Ecological Classification Standard (CMECS)*, Tech. Rep., NatureServe, Arlington, Virginia, to suit the purpose of the LSLR discussion.

where ϑ, λ, and t are co-latitude, longitude, and time, respectively, ρ_W and ρ_L are the densities of the ocean water and the load on land (water or ice), respectively, G is the Green's function for LSL defined below, O the ocean function, defined to be one over ocean and zero over land, and η the accumulated ice load change due to mass added or removed from land. $c(t)$ is determined such that mass is conserved. ξ as defined by eqn [6] is a continuation of LSL onto the continents, and the true LSL has to be defined as $\hat{\xi} := O\xi$. The function ξ has the important advantage over $\hat{\xi}$ of being continuous at the coastlines. The mass-LSL eqn [6] assumes instantaneous distribution of the water in the global ocean and thus is only valid for sufficiently long time scales. Hydrodynamic studies showed that the equation is appropriate at annual to longer time scales (see Plag 2006b; and the reference therein). Over the last two decades, eqn [6] has been augmented by several groups (e.g., Milne et al. 1999), with the most comprehensive version (Mitrovica and Milne 2003; Kendall et al. 2005) accounting for melt-water inundation of deglaciated areas and rotational effects of LSL changes (pole tide) in a self-consistent manner. There are many technical details related to the use of eqn [6], including the Earth model, the ice history, and numerical procedures which are discussed e.g., in Plag et al. (1998); Mitrovica et al. (2010).

The mass-LSL eqn [6] has been applied extensively to studies of LSL changes caused by the ice ages and the subsequent Postglacial Rebound (PGR) (see Mitrovica et al. 2006; and the references therein). In the PGR studies, main focus has been on the viscous part and the determination of the radial viscosity profile of the Earth mantle (e.g., Peltier 1974; Farrell and Clark 1976; Nakada and Lambeck 1987; Mitrovica et al. 1994a,b; Vermeersen et al. 1996). There are still considerable inter-model differences in predictions of present-day PGR signals in LSL, surface displacements, geoid, and rotation (e.g., Chambers et al. 2009), which originate mainly in differences in ice history and the treatment of rotational effects. Using eqn [6] to describe the relation between present-day mass changes and LSL so far has been restricted to a few examples (e.g., Plag and Jüttner 2001; Mitrovica et al. 2001; Plag 2006a; Mitrovica et al. 2009; Bamber et al. 2009). It has to be noted that in many scientific communities outside the solid Earth sciences, the very large spatial variations of LSL compared to the global average are not well known and often ignored in GSLR impact studies.

Major mass redistribution in the global water cycle can result from significant mass loss from ice sheets, ice caps, and glaciers. Net ice-mass depletion of land-based ice will add to the net water mass in the ocean, unless it is intercepted by surface water or terrestrial storage reservoirs. The mass loss is accomplished by direct climate forcing (through changes in precipitation, melt rate, etc) and by dynamic changes (e.g., subglacial sliding, iceberg calving) that can be indirectly and non-linearly influenced by climate. Dynamic changes can act to accelerate mass loss from glaciers and ice sheets, but generally not to retard it. If these mass changes are known sufficiently, for example, from model predictions, then the resulting LSL variations can be calculated using eqn [6]. However, there are differences in the LSL admittance functions (e.g., the global pattern of LSL change caused by a 1 m unit ice change over an ice sheet or glacier normalized by the globally averaged LSL change) computed by different groups for the GIS and AIS. For example, the global admittance functions for the AIS and GIS computed by Plag and Jüttner (2001) exhibit larger spatial variability than those computed by Mitrovica et al. (2001, 2009) and Vermeersen et al. (2008, personnel communication). Due to a lack of abundant modern observations close to sufficiently large and rapidly changing ice masses, a comparison of near-field concurrent LSL changes to predictions has not been possible so far. Thus, the solutions of the elastic part of eqn [6] have not been validated against observations. Results of a recent study of near-field vertical uplift induced by present-day ice load changes in Svalbard (Kierulf et al. 2009) indicate near-field values for the LSL admittance function in the range of −50 to −70, which would require a much larger spatial variability of the LSL admittance function than predicted by Mitrovica et al. (2001, 2009), but somewhat smaller than what Plag and Jüttner (2001) predict. The origin of the inter-model discrepancies can be in the Earth model itself; the computation of the Load Love Numbers (LLNs) and the parameterization of the Earth model for this computation; the convolution of the Green's function with the load anomalies; and the solution of the mass-LSL equation. The availability of increasingly dense GPS networks in the vicinity of rapidly changing ice loads provides a unique opportunity to identify the origin of the inter-model differences and to resolve them.

Best estimates for the total present-day volume of land-based ice are: for the East Antarctic Ice Sheet (EAIS), ca. 70 m Sea-Level Equivalent (SLE); for the West Antarctic Ice Sheet (WAIS), ca. 3.3 m SLE (Bamber et al. 2009); for the GIS, ca. 7.2 m SLE (Bamber et al. 2001); and for the aggregate of all other glaciers and ice caps world-wide, ca. 0.6 m SLE (Radic and Hock 2010). Current and next-century contributions from the EAIS are believed to be comparatively small, while the WAIS and GIS are large present-day sea-level contributors, at ca. 0.5 and 0.74 mm year^{-1} SLE, respectively (Rignot et al. 2008a,b); The total aggregated contribution of GIC to SLE volume is small, but the GIC are presently a very large source of sea-level rise, at ca. 1.1 mm year^{-1} (Meier et al. 2007), although Jacob et al. (2012) reach a much reduced estimate of 0.41 ± 0.08 mm year^{-1}. The large loss rate from GIC is diminishing the source volume at a rate of close to 0.2%, so reservoir depletion will eventually reduce the GIC flux, but not significantly in the near term (next century). Jacob et al. (2012) estimate the current total contribution of GIC and the two large ice sheets to be 1.48 ± 0.26 mm year^{-1}.

Prediction of GSL from land-ice sources depends critically upon numerical simulations and requires knowledge of atmospheric and oceanic forcing, as well as, geometric landscape boundary conditions. While significant progress has been made in ice sheet numerical modeling capacity, robust operational models do not yet exist for prediction. Chief among obstacles to be overcome are a lack of knowledge of the processes of subglacial sliding (boundary slip) and iceberg calving. Comprehensive global predictive modeling is also hindered by a lack of basic information for ca. 40% of the GIC area, including glacier and ice cap volume, basal topography, and location of marine-based outlets (Pfeffer et al. 2008).

4.14.3.5 Impacts of Sea-Level Rise

Coastal zones are complex and dynamic environments with many interactions between physical processes, such as waves and tidal currents, imposed on underlying geology, the availability of sediments, and changes in sea-level. The spatial variations in these factors lead to a wide variety in the characteristic coastal landforms, including beaches, cliffs, and barrier islands. The general response of coastal landforms that can occur in response to LSLR are widely understood (e.g., FitzGerald et al. 2008), but determining precisely how and what changes occur in response to a specific rise in sea-level has been difficult, due to the wide range of spatial and temporal scales involved in the processes that cause the LSLR and interact at a given coastal location. Consequently, it has been difficult to determine a quantitative relationship between LSLR and shoreline change. No scientific consensus has been reached as to whether or not observed shoreline changes can be quantitatively related to LSLR (Gutierrez et al. 2009; and the references therein).

Focusing on coastal ecosystems, the impacts of LSLR (in combination with other sea-level hazards) can be broadly classified into effects of (1) wetland loss, (2) salinity increases, and (3) beach erosion (Titus 1988). LSLR is a coastal hazard with the potential to amplify the impacts of waves, storm surges, shoreline erosion, wetland loss, and saltwater intrusions. Even a small increase in LSL can change the statistics of extreme sea-level events significantly. Depending on the coastal topography, what today is a 100-year flood could easily become a 10-year flood or an even more frequent flood.

Many recent assessments of the coastal impacts of LSLR have focused on identifying land located at elevations below plausible LSL trajectories (e.g., Anthoff et al. 2006; Rowley et al. 2007; CCSP 2008). While these elevation-based analyses are an important first step in the understanding of the potential impacts of LSLR, this approach only reveals a part of the potential consequences for the coastal zone. Changes in the coastal zone are driven by interrelated, complex processes including waves, tsunamis, storms, LSLR, sediment transport, and biological processes acting on a wide range to temporal scales. As a result, the response of a coastal region to LSLR results from a combination of one or more of the processes in the following broad categories (e.g., FitzGerald et al. 2008): increased frequency of storm flooding; land loss due to permanent inundation of low-lying lands; land loss due to erosion of beaches, dunes, and cliffs; barrier island breaching, segmentation, and migration; wetland conversion to open water, migration inland, and accretion through increased flooding; expansion of estuaries; saltwater intrusion into freshwater aquifers and surface waters.

Even the lowest GSLR scenarios considered in the IPCC AR4 would have a wide range of impacts on many coastal environments and infrastructure. Effects are likely to include coastal erosion, wetland and coastal plain flooding, salinization of aquifers and soils, and a loss of habitats for fish, birds, and other wildlife and plants (Meehl et al. 2007). IPCC estimates that a continuation of the current GSLR likely would lead to a loss of as much as 33% of coastal land and wetland habitats in the next hundred years. Considering that the impacts in most areas do not scale linearly with the sea-level rise (Craft et al. 2009), any increase in the rate of GSLR could increase land and habitat losses dramatically, putting a very large number of wetland and swamp species at serious risk. In the polar regions, the retreat of coastal sea ice is already threatening species that depend on the existence of sea ice with extinction (Arctic Climate Impact Assessment (ACIA) 2004).

4.14.3.6 Coastal Protection

If coasts come under increasing threats from inundation, flooding, and increased erosion, mitigation of LSLR impacts and adaptation strategies are needed. Coastal protections, such as sea walls and dikes, have been constructed since Roman times to protect human settlements from the sea. In the twentieth century, large parts of the low-lying coasts have been protected with massive so-called 'hard' engineered defenses, particularly in Europe and North America. Disasters caused by storm surges such as the 31 January 1953 event in The Netherlands, Belgium, and the United Kingdom triggered many national programs to strengthen coastal protection. This 'hold-the-line' approach and the security provided by these protections has enabled and encouraged development of coastal regions otherwise at risk of flooding (**Figure 9**). Following this line, many economic assessments conclude that the only viable strategy is to improve coastal protection by improving the engineered defenses (e.g., Schwerzmann and Mehlorn 2009).

It is, however, now increasingly recognized that these hard defenses are unsustainable for several reasons (Turner et al. 2007). In the case of failure, the ensuing disaster is severe, as was illustrated by the impact of Hurricane Katrina in New Orleans. In many cases, the protections themselves have led to a reduction or loss of intertidal habitat, reducing also the natural protection these compartments often provide. Coastal habitat migration, loss and gain in response to sea-level changes have occurred throughout geological times. However, the perspective for the twenty-first century is different due to the presence of developed shorelines, which introduces a new barrier for habitat migration. Moreover, the rate of LSLR could be at the upper end of the spectrum (see Section 4.14.3.2).

We can distinguish between five generic strategies for dealing with coastal defense in areas with rising sea-level, with different impacts on ecosystems, society, and economy (**Figure 10**). (S1) Do nothing: inaction eventually will lead to abandonment and destruction of infrastructure built within the zone inundated by the rising sea. This will leave room for the tidal zone to migrate inland. (S2) Managed realignment: plan infrastructure in the potentially inundated areas such that it can be realigned if sea-level rise and shoreline transgression requires this. This also leaves room for the tidal zone to migrate inland. (S3) Hold-the-line: hard engineered protections (seawalls, dikes, barriers) are constructed to prevent transgression of the shoreline. Over time, this eliminates the tidal zone completely. (S4) Progression: new defenses are constructed seaward of the original shoreline, thus creating new land and protecting existing infrastructure. This approach generally leads to reorganization of ecosystems. (S5) Soft intervention: the ability of ecosystems to migrate vertically is utilized to raise parts of the tidal zone and the adjacent land vertically. Not all of these strategies are applicable to all sites.

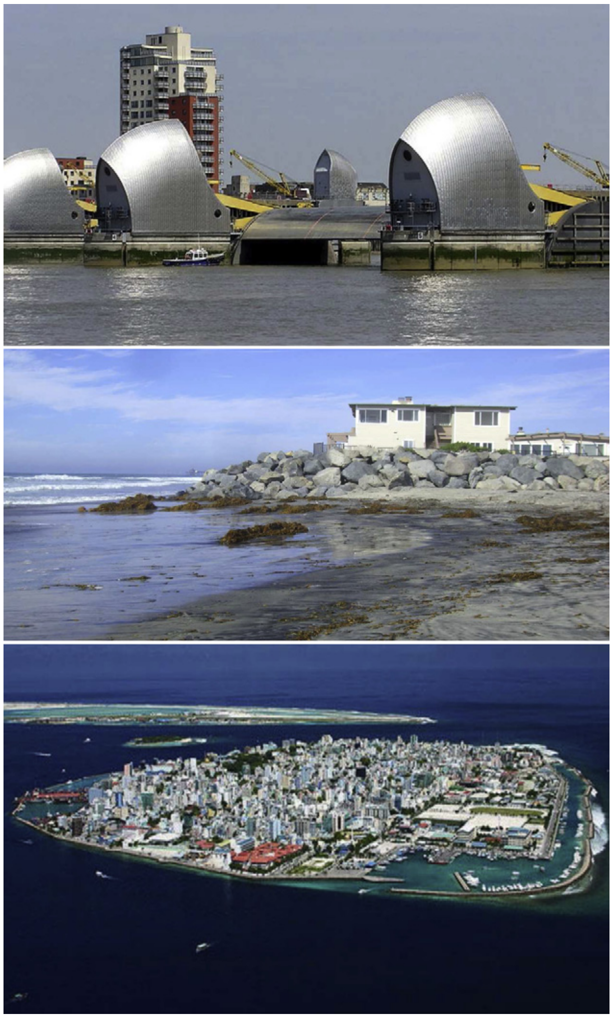

Figure 9 Examples of coastal protection and developments. Upper picture: the Thames Barrier, London, U.K., which is protecting more than 800 000 houses in the flood plane, including crucial infrastructure such as about 50 hospitals; Middle: Imperial Beach, California, where houses at a transgressive beach in a tsunami-prone area are protected with boulders, while the beach is transgressing past the developed coastline. Bottom: The island of Malé, capital of the Maldives Islands in the Indian Ocean. The maximum elevation is 2.4 m, and population is around 100 000. This extreme example of the hold-the-line (or even progression) strategy (**Figure 10**) required a seawall around the entire island.

For example, in urban coastal areas such as London, New York City, Jakarta, Shanghai, and Malé, Maldives (Figure 9), the strategies (S1) and (S2) may not be viable alternatives for economic and social reasons. For urban areas in deltas, storm surge barriers (S3) are an option to handle extreme events. The protection of world heritages (such as the city of Venice) may also require floodgates with potentially significant impacts on the marine ecosystems. The applicability of the strategies also depends on the rate and amount of LSLR. The very rapid subsidence in parts of Jakarta eventually may only leave (S2) as an option, while a significant LSLR only will leave (S1) for the Maldives. In rural coastal areas, the negative ecological impact of (S3) or (S4) may exceed the social and economic impact of living within the future flood plain resulting from a projected LSLR. Economic and social conditions impact the choice, too. In many developing countries, (S1) and partly (S2) are the only viable options.

Considering the impact on ecosystems, strategies (S1), (S2), and (S5) are the least impacting. In general terms, the potential ecological effects of strategies (S3) and (S4) involving hard coastal protections are understood (e.g., Seitz et al. 2006). Likewise, the impact of an LSLR on ecosystems has been studied abundantly. However, few studies on the combined effect of LSLR and coastal protections have been published (Shellenbarger Jones et al. 2009). Nevertheless, it can be stated that hard engineered protection combined with sea-level rise would narrow down or eliminate most of the tidal zone and the adjacent wetlands. Similar to developed coastlines, these protections would prohibit inland migration of the sea-side coastal zone compartments in response to LSLR.

Turner et al. (2007) considered managed realignment as an alternative to maintaining 'hard' defenses for the protection of land from LSLR. In this approach, the engineered defenses are deliberately breached, thus allowing the coastline to recede to a new shoreline further inland, where a new intertidal habitat is created providing natural protection from flooding and erosion. Their cost–benefit analysis shows that managed realignment can be economically more efficient than holding-the-line, if the time period considered is sufficiently long (generally greater than 25 years). Particularly for rapid rates of LSLR, managed alignment may be the only viable options both for ecosystems and for human population.

4.14.4 The Assets: Coastal Ecosystems and Their Services

The assets of the coastal zone include geomorphological features, as well as, coastal ecosystems. Depending on the geological and environmental settings, coastal ecosystems include tidal marshes, tidal forests, aquatic vegetation beds, tidal flats, beaches, cliffs, and estuaries (Shellenbarger Jones et al. 2009). Providing habitat for many species (including many endangered and threatened species), the coastal ecosystems are among the most productive ones and they provide essential ecosystem services that no other ecosystem can provide (Daily et al. 1997; de Groot et al. 2002). These services include not only those processes supporting the ecosystem itself but also many human benefits derived from those processes. The wide range of services include nutrient cycling and uptake, natural water quality improvement, water storage and delivery, flood protection, shoreline erosion control, fish production, and the provision of recreational opportunities helping to promote human well-being.

Wetland plants hold the soil in place with their roots, absorb the energy of waves, and reduce the impact of tidal streams. They provide a buffer to major storm impacts, particularly to damaging storm surges, and thus reduce coastal erosion.

Tidal marshes and mangroves can store flood waters that runoff from upland. By retaining excess nutrients and some pollutants in surface-water runoff from higher dry land before the runoff reaches open water, they provide an important filter service, and reduce sediment that otherwise would degrade

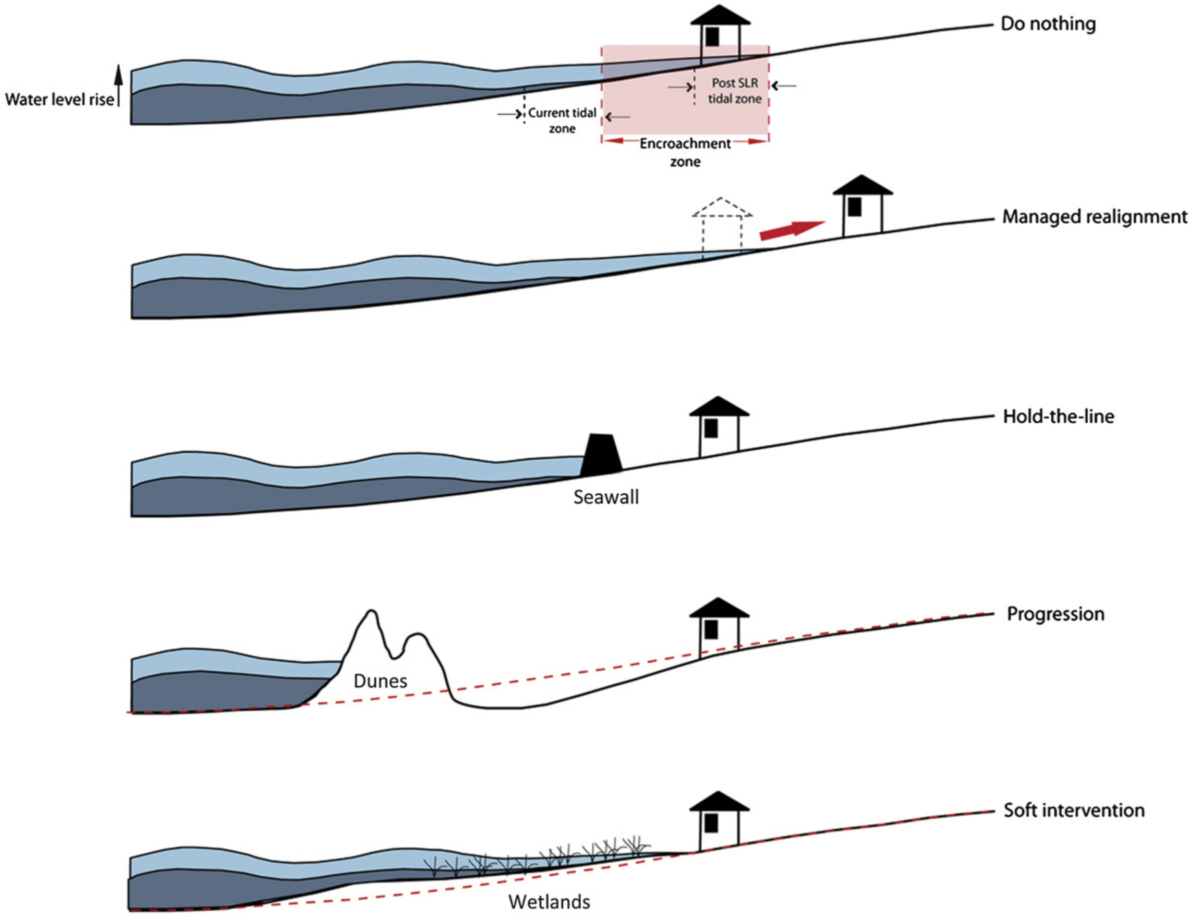

Figure 10 Five generic strategies for coastal management in areas with potentially rising sea levels.

estuarine and adjacent marine compartments and impact fish and amphibian egg development.

Estuarine, marine fish, and shellfish depend on coastal wetlands to survival. The wetlands are critical for juvenile and adult stages of many economically important marine fish and shellfish species. In fact, most commercial and game fish breed in coastal marshes and estuaries. Various birds and certain mammals, many of them with economic value, also depend crucially on coastal wetlands.

For many coastal communities, wetlands, estuaries, and the adjacent marine zone contribute to the economic livelihoods. Coastal wetlands have recreational, historical, scientific, and cultural values, and they offer significant esthetic value to humans. Estimates of the global economic value of all the services coastal wetlands provide are in excess of $1.6 Trillion per year (Costanza et al. 1997). Particularly, the recreational opportunities are economically important. There is an estimated half of international tourists travel to wetlands of all types, particularly those in the coastal zone.

The marine and coastal zone wetlands can be separated into the following:

1. Marine waters: permanent shallow waters less than 6 m deep at low tide; includes sea bays, straits;
2. Subtidal aquatic beds: sea grasses, tropical marine meadows;
3. Coral reefs;
4. Rocky marine shores: rocky offshore islands, sea cliffs;
5. Sand, shingle, or pebble beaches: sand bars, spits, sandy islets;
6. Intertidal mud, sand, or salt flats;
7. Intertidal marshes: salt marshes, salt meadows, raised salt marshes, tidal brackish, and freshwater marshes;
8. Intertidal forested wetlands: mangrove swamps, swamps, tidal freshwater swamp forests;
9. Brackish to saline lagoons and marshes with one or more relatively narrow connections with the sea;
10. Freshwater lagoons and marshes in the coastal zone;
11. Non-tidal freshwater forested wetlands.

Mangroves are an important component of the coastal wetlands. Mangrove distribution in latitude is controlled by temperature. Perennial mangroves generally cannot survive temperatures below freezing, constraining their occurrence to the tropics and subtropics with maximum development between 25 °N and 25 °S. The richest mangrove communities occur in areas where maximum water temperatures exceed 24 °C. The most recent estimates suggest that mangroves presently occupy about 146 530 km^2 of tropical and subtropical coastline (McLeod and Salm 2006). Mangroves provide the entire ecosystem services mentioned above, and they provide income from the collection of mollusks, crustaceans, and fish, and the harvest of firewood, timber, and wood chips.

Despite the recognized value of coastal ecosystems, the loss of coastal wetlands over the last few decades has been severe. The cumulative effects of natural and anthropogenic pressures have turned mangrove wetlands into one of the most threatened ecosystems worldwide. About 50% of the global area has been lost since 1900 and 35% in the past two decades, primarily due to human activities, such as conversion for aquaculture. The global average annual rate of mangrove loss is about 2.1% (Gilman et al. 2006a). Over the last few decades, coastal wetlands were reduced globally by 30%. Protecting wetlands is important for humanities safety and welfare. This was recognized in the last century, and in 1971 the Convention on Wetlands of International Importance, called the Ramsar Convention, was adopted in the Iranian city of Ramsar. The Ramsar Convention's mission is "the conservation and wise use of all wetlands through local and national actions and international cooperation, as a contribution toward achieving sustainable development throughout the world." The definition of wetlands in the Convention is broad, including lakes and rivers, swamps and marshes, wet grasslands and peatlands, oases, estuaries, deltas and tidal flats, near-shore marine areas, mangroves and coral reefs, and human-made sites such as fish ponds, rice paddies, reservoirs, and salt pans. The wise use of wetlands, defined as "the maintenance of their ecological character, achieved through the implementation of ecosystem approaches, within the context of sustainable development," aims at the conservation and sustainable use of wetlands and their resources, for the benefit of humankind.

Coral reefs are very valuable and diverse ecosystems providing food and habitat for many other species. In addition to their ecological services, these systems provide billions of dollars in services including tourism, fish breeding habitat, and protection of coastlines. The coral reefs face many challenges arising from anthropogenic activities such as pollution, destructive fishing, poorly regulated tourism, and ocean acidification, as well as, from changes in local and regional weather, which over the last 30 years have led to the death or severe damage of about one-third of the world's corals (Janetos et al. 2008).

The quest to understanding how shorelines form and how human activities affect these processes has led to the creation of a number of classification schemes (e.g., Anderson et al. 1976; Cowardin et al. 1979; Cowardin and Golet 1995; Kutcher et al. 2005; Madden and Goodin 2007; Lund and Wilbur 2007). Most of the authors group coastal areas into classes that have similar features, as a result of having developed in similar geological and environmental settings. Detailed inventories available for certain regions may characterize the shore zone using shoreline morphology, substrate, wave exposure, and biota and subdivide the coast into more or less homogeneous units (e.g., Berry et al. 2001), while others use less granular and more descriptive approaches (e.g., ACCC 2006).

A separation in the main regimes based on the Coastal Marine Ecological Classification Standard (CMECS) as used in Madden and Goodin (2007) is provided in Table 2. The boundaries of CMECS are explicitly defined from the supratidal zone to the central oceans. For the discussion of LSLR impacts, we also have to include the dry land above the high water mark, to which the supratidal zone and, potentially, other zones relocate in case of the rising sea-level. The CMECS considers the following six levels:

- Level 1: Regime: differentiated by a combination of salinity, geomorphology, and depth;
- Level 2: Formation: large physical structures formed by either water or solid substrate within systems; including geoforms and hydroforms such as lagoons, embayments, deltas, reefs, seamounts, islands, ocean gyres, upwellings, etc.;
- Level 3: Zone: the water column, littoral or bottom; position with reference to the water: whether it is a continuously submerged bottom or at the waterline (littoral), or entirely within the water column (pelagic);
- Level 4: Macrohabitat: mesoscale physical structures that contain multiple habitats;
- Level 5: Habitat: a specific, repeatable combination of physical and other environmental characteristics that tend to co-occur;
- Level 6: Biotope: the characteristic dominant association of attached, sessile, or sedentary biota; the smallest quantum unit of the habitat in CMECS.

4.14.5 Vulnerabilities: Impact of Sea-Level Change and Coastal Protection on Coastal Ecosystems

As mentioned in the introduction, the concept of vulnerability differs between scientific disciplines (Brooks 2003). While we use here the concept mostly applied to natural hazards and their impact on the built environment and the population in this environment, we acknowledge that the vulnerability of ecosystems is comparable to that of social system. For these systems, the concept of a threshold is important, that is, the possibility that the system collapses if a certain stress level is exceeded.

While we can provide a concise typology of the physically defined sea-level hazards (see Section 4.14.3), it is more difficult to define the relationship between a given hazard and the vulnerability and adaptive capacity of a human system or ecosystem, as these depend critically on the nature of the hazard faced. As expressed in Section 4.14.2, vulnerability of a system (human or ecosystem) is time variable and depends on the capability of the system to adapt in a timely manner to changing hazards. It also depends on the level of stress the system is already exposed to.

Most of the coastal ecosystems discussed in the previous section, such as sea grass meadows, coral reefs, rocky intertidal zones, mangroves and other wetlands, and estuarine communities, are structured around sea-level. Many of these ecosystems are already stressed by coastal development, eutrophication, and industrial pollution. These impacts reduce the resilience of the ecosystems to recover from disturbances. A rapid LSLR is a disturbance that many coastal ecosystems might face in the coming decades. There are many unanswered questions regarding the resilience of coastal ecosystems with respect to rapid LSLR.

Human activity has been the major threat to wetlands. This is also true for coastal wetlands. Conversion for aquaculture, pollution through agriculture, industrial development, and urban and suburban sprawl in the coastal zone has caused the greatest losses of coastal wetlands. In many areas, the biggest source of loss for freshwater coastal wetlands is from urban sprawl. In some areas, the primary source of saltwater wetland loss is a rise in LSL caused by land subsidence associated with mining of oil, gas, and groundwater. Coastal protection and urban development often narrow down the area in which wetlands can exist or migrate into, if changes in the shoreline due to erosion or LSLR require this.

Estuarine wetlands are dependent upon freshwater inflow from rivers. In some estuaries, freshwater inflow has been reduced through river regulations and rerouting. In many deltas, sediment influx is needed to compensate for subsidence of the delta, and river regulations often reduce the influx, leading to subsidence and the permanent drowning of wetlands. An example are the Everglades in Florida, where human interventions changed the freshwater influx (Walker and Salt 2006), and LSLR increases the salt content of existing bodies of freshwater. Local rainfall also has been reduced in this region, at least in part due to land use change in the Everglades area (Marshall et al. 2004), with a resultant reduced flux of freshwater into the coastal waters.

LSLR would add stress to the already stressed coastal wetlands. The main vulnerability of coastal ecosystems to LSLR result from changes in the physical and dynamical environment, leading to increased coastal erosion, more extensive coastal inundation, and higher storm-surge flooding; changes in the location of the different regimes through landward intrusion of sea water in estuaries and aquifers; inhibition of primary production processes through elimination of crucial ecosystems. It is important to note that most of these impacts do not scale linearly with LSLR (Craft et al. 2009).

Other climate-change related processes can increase the stress, e.g., through changes in surface-water quality and groundwater characteristics, changes in the distribution of pathogenic microorganisms, also in combination with higher sea surface and sea water temperatures, and, for the polar regions, reduction of sea-ice cover.

Coastal wetlands have two main adaptation strategies: vertical migration and horizontal migration. Vertical migration requires sufficient influx of sediments that can be captured within the ecosystem and helps to raise the base to compensate for an LSLR. Migratory organisms will most likely be able to adapt to a sufficiently slow LSLR if there is space for migration. More rapid rates of LSLR may lead to changes that may hamper the successful migration of a number of organisms. If coastal LSL continues to rise, low-lying wetlands would be permanently inundated, and ecosystems in these areas would be flooded. Formerly dry land would turn into wetland. This would impact significantly the structure and function of the coastal and inland ecosystems and impact their capabilities to perform ecosystem services.

Moreover, adaptation by an ecosystem may be inhibited by processes originating outside the ecosystem. Understanding the vulnerability requires to consider ‘external’ obstacles to adaptation. Coastal development creates obstacles to ecosystems as they are trying to adapt to changes in the environmental conditions. For example, along the coasts of Denmark, Germany, and The Netherlands, dikes built to protect the land against storm surges increasingly narrow the mud-flats in the Watt and hinder ecosystems to move further inland. The increase of storm surge heights of up to 1 m predicted for most of these coast by Schwerzmann and Mehlorn (2009) and others will likely lead to more flood protections. In combination with a possible LSLR, this prediction-based adaptation would lead to a significant reduction of the unique Watt ecosystems.

In many coastal areas, wetlands and mangrove forests act as buffers to storm surges and tidal waves. In Bangladesh and Thailand, these natural coastal protections are already submerged by rising sea-levels. Normally, the mangroves would re-establish themselves at the new low-tide zone, and wetlands would migrate inland. However, in large parts of these coasts, buildings and other types of development on the coast are blocking them. As a result, interaction of LSLR and coastal protection causes a reduction of the valuable ecosystems.

LSLR is one of the greatest challenges for mangrove ecosystems (McLeod and Salm 2006). If LSLR is slow enough, then mangroves can adapt if adequate expansion space exists, and if other environmental conditions are met. If LSL is rising, the seaward and landward margins of the mangrove would have to migrate landward in order to maintain the preferred environmental conditions (period, frequency, and depth of inundation and salinity). Whether or not such a migration is successful or even possible depends on the rate of LSLR, the slope of adjacent land, sediment composition of the upland habitat, and the absence of obstacles (seawalls and other shoreline protection structures) to landward migration. In some locations, the lateral extent of mangrove would narrow down or the LSLR would lead to complete removal. What rates of LSLR would exceed the capabilities of mangroves to adapt? The answer depends on the location, but several studies indicate that in some locations $LSLR_{100}$ values of 0.12 m per century would be too much (Ellison and Stoddart 1991), while in other locations mangroves have adapted to rates of 0.25 m per century. However, we have no indication that mangroves would be able to adopt to $LSLR_{100}$ values of 0.5 m per century or more.

LSLR also would add to the stress on wild fish stocks by narrowing down crucial areas for juvenile and adult stages of many economically important marine fish and shellfish species. This would add to increasing stress due to ocean acidification, which weakens the ability of shellfish, corals, and marine phytoplankton to form their skeletons, increasing nutrient loads and pollution.

Healthy coral reefs could likely keep up with a moderate LSLR, but many reefs are already severely degraded by the effects of coral bleaching, UV-B radiation, pollution, and ocean acidification. Future increases of sea surface temperature will very likely increase stress on coral reefs, reducing their ability to compensate for LSLR.

There is a high risk that the combined stress of anthropogenic activities, climate effects, and LSLR could lead to the crossing of certain thresholds and a dramatic loss of biodiversity and degradation of services from marine and coastal ecosystems. As discussed in Section 4.14.3.2, the rates of changes in critical Earth system parameters are far outside rates experienced in the past, and coastal ecosystems might not be resilient with respect to these unprecedented disturbances.

4.14.6 Risk Assessments

As stated in Section 4.14.2, we define risk as probability, times vulnerability of assets, and times value of exposed assets. For the probability of LSLR, we have established in Section 4.14.3.2 that it is possible that for many locations (see **Figure 3**), twenty-first century LSLR_{100} could exceed 0.5 m. There is a moderate probability that many locations could experience far more extreme LSLR_{100} values in excess of 1 m. If the main contribution to a rapid rise would come from increased melting of both the GIS and the AIS, then low-latitude LSLR would be largest, while LSLR in many polar regions would be negative (e.g., sea-level would fall). If only one of the two ice sheets would have a large contribution, then sea-level would fall in the near-field of this ice sheet, and rise more than average in the opposite polar region. However, mangroves and coral reefs in the tropics and sub-tropics likely would experience a rapid rise. We also concluded that the possibility of a catastrophic LSLR of more than 2 m per century cannot be excluded for many regions particularly at low latitudes.

In Section 4.14.4 The Assets: Coastal Ecosystems and Their Services, we have underlined the high ecological, social, and economic value of coastal ecosystems. Taking the economic value alone, the estimated value of the services of coastal ecosystems is on the order of $1.6 trillion per year (Costanza et al. 1997).

The vulnerability discussion in Section 4.14.5 indicated that many of the coastal ecosystems are pre-stressed, while their capacity to adapt to LSLR is limited due to human interferences. In many cases, resilience to rapid LSLR is greatly reduced.

If we conservatively assume that for 20% of the coastal ecosystems a 21st LSLR_{100} of 0.5 m would cross a threshold leading to the complete loss of the ecosystem services, and if we further arbitrarily assume that such a rise has a probability of 0.8, then we are exposed to a risk of \$250 000 year^{-1}. A more detailed computation of the LSLR-related risk of ecosystems could be done using eqn [1]. However, due to the quantitative uncertainties in the location-dependent PDF of LSLR, the location-dependent vulnerability of the ecosystems (which depends on many factors) and the location-dependent service values would only allow an order of magnitude estimate. What we can say is that the possible 21st LSLR will lead to a reduction of the coastal ecosystem services exceeding \$250 Billion year^{-1} toward the end of the century.

4.14.7 Adaptation and Mitigation – Recommendations

During the last century, a common strategy for mitigation of sea-level hazards was (S3) (**Figure 10**), e.g., the 'hold-the-line' approach based on hard engineered coastal defenses. This approach likely would acerbate the impact of a rapid LSLR on ecosystems. It is therefore necessary to reconsider the mitigation-based approach and, where possible, to progress toward an adaptation-focused approach. The corresponding generic strategies are (S1), (S2), and (S5). In many locations, the 'do nothing' (S1) and 'managed realignment' (S2) strategies are those with the least costs in terms of lost ecosystem services, but highest in costs in terms of infrastructure and social impact. 'Soft intervention' (S5) could turn out to provide the most balanced approach, which is a hybrid of mitigation and adaptation.

Importantly, the planning for the adaptation strategy has to start as early as possible. By responsible land use planning, with limited development of those low-lying areas that likely will turn into future floodplains or areas that are need for migration of coastal ecosystems, we can keep strategies (S1) and (S2) viable. The underlying vision for the development of most low-lying coastal land areas should be based on the premise that eventually this land could give way to a rising sea. By carefully managing the factors that impact the ability of coastal ecosystems to migrate vertically, we can prepare for (S5).

The decision of where to apply the adaptation strategies (S1), (S2), and (S5) should be based on a detailed assessment of the coastal ecosystems, their specific service functions and value, and their resilience to rapid LSLR. These assessments should be carried out based on a widely accepted best practice. For many countries, this assessment would require capacity building in order to collect the required information and to carry out the assessments.

The uncertainty of GSLR projections and the fact that we cannot exclude a GSLR significantly larger than what current models can predict render long-term (century-scale) projections almost useless for planning. What is needed is an approach based on monitoring of the Earth system and forecasting of LSLR on decadal time scales, if such a model can even be developed (Plag et al. 2010). This would constitute an early warning system capable of detecting the onset of a rapid GSLR, e.g., by detecting an accelerated melting of one of the large ice sheets. Such a sea-level monitoring and forecasting service is comparable to a smoke-detector, which is a standard approach to identify a low-probability, high-impact event of a fire in a timely manner. Building such a service through international cooperation (comparable to the approach taken in the field of meteorology) would be of particular value for those countries where capabilities in analyzing and forecasting the relevant processes are not sufficiently developed. Capacity building for necessary in situ observations in the coastal zone should be a priority.

The value of coastal ecosystems and their conservation is often underestimated, especially in less developed countries, where high population growth and development pressure create a focus on short-term economic gains and a neglect of long-term economic necessities. A dedicated outreach is needed to better inform decision makers and the public about the value of coastal ecosystems and the extreme risk associated with the sea-level rise. There is also a need to develop new approaches to the dialog between science and society in order to allow for the development of an informed risk perception. Importantly, the currently common one-way interaction between science and practice needs to be augmented by feedback to science from the practitioners (Vogel et al. 2007).

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4.15 The Vulnerability of Biodiversity to Rapid Climate Change

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Glossary

Adaptive capacity Species and system potential for resistance and resilience to environmental change; where resistance is the ability to resist a change in state and resilience is the ability to recover from a change in state following a perturbation.

Biological diversity (biodiversity) Complexity in biotic composition, structure, and function considered at levels of species (and their genetics), communities, ecosystems, landscapes, and broader scales.

Microevolution Evolutionary change (change in gene frequency over generations) within a species or its populations.

Rapid climate change In the context of this chapter, all features of local and regional surface climate whose attributes may plausibly vary over decadal through centennial scales at rates disruptive to the ecology of species and their physical and biotic environments.

Vulnerability System or species sensitivity to an environmental change relative to level of exposure to that threat.

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4.15.1 Introduction

Over recent decades, conservation biologists and land stewards have become increasingly aware of the need to incorporate rapid changes in climate as a threat to biological diversity ('biodiversity') in planning and management (Comer et al. 2012; Game et al. 2010; Glick et al. 2011; Hannah et al. 2002a; Hansen et al. 2003; Joyce et al. 2009; Mawdsley et al. 2009; National Park Service 2010). This need has intensified as we better understand the multidimensional vulnerability of the biosphere to this and other threats (Rosenzweig et al. 2007; Walther et al. 2002) and the societal consequences of biodiversity loss to ecosystem services (Chapin et al. 2000; Fischlin et al. 2007). Simultaneously, we better appreciate the large uncertainties in foreseeing future states of species and their landscapes and corresponding difficulties in incorporating vulnerability to changing climatic conditions in natural resource management plans (Kittel et al. 2011c; Lawler et al. 2010).

The chapter starts by presenting generalized outlooks for and uncertainties in climatic and biotic futures to provide context for discussions in subsequent sections (see Section 4.15.2). The core of the chapter is a review of key aspects of the vulnerability of biodiversity to climate change, considered from species – and their genetics – through community and ecosystem dynamics (see Section 4.15.3). My thesis is that this vulnerability is highly complex – running through all levels of biodiversity – and arises from ecological and evolutionary processes that are strongly interactive, span a wide range of temporal and spatial scales, and are context dependent. Inherent limitations in predicting outcomes of such complex dynamics, coupled with uncertainties in future forcings, make it difficult at best to anticipate specific consequences of this vulnerability. The chapter concludes by presenting strategies for handling such uncertainty in conservation planning (see Section 4.15.4).

4.15.2 Outlooks for Future Environments

4.15.2.1 Future Climate: Outlooks and Uncertainty

The vulnerability of species or ecosystems can be considered in terms of resistance (to changing state) and resilience (ability to recover) to changing climatic conditions and so are relative to the magnitude of the threat. In this regard, I refer to 'rapid climate change' as meaning all features of local and regional surface climate whose attributes may plausibly vary over decadal through centennial scales at rates disruptive to the ecology of species and their physical and biotic environments. An assessment of the vulnerability of current biodiversity to such variation will only be useful to the extent we can specify what the spectrum of plausible future climates might be. For this, we can look to three approaches: historical shifts, model sensitivity, and novel possibilities. The bottom line is that these approaches provide key insights and yet have high uncertainty associated with their spatial and temporal outlooks.

4.15.2.1.1 Historical Understanding

Forward-looking biotic assessments can draw from analyses of historic periods with rapid climate shifts, such as multidecadal climatic (and linked ecological) regime changes (e.g., the Pacific Decadal Oscillation; Mantua et al. 1997; Pederson et al. 2006). Such an analog approach asks what would be the status of biodiversity if regional climates were to undergo shifts today similar to those observed over past periods, and looks from this point forward, placing these changes in the context of additional threats such as invasive species, exploitation, and habitat degradation.

The primary advantage of the historical approach is that it provides an observation-based assessment of biotic sensitivity to a known forcing. A key limitation is that the past is an imperfect analog of the future – that is, future changes will likely differ in magnitude and character from those in historical or paleo records.

4.15.2.1.2 Guarded Lessons from Modeling

We can glean overarching lessons from climate model sensitivity studies, such as under scenarios of increasing greenhouse gases, sulfate aerosols, and land cover change (e.g., Avila et al. 2012; Feddema et al. 2005; Meehl et al. 2007). Caution is needed, however, in extracting these lessons because of high uncertainty associated with model projections. By 'high,' I mean where the uncertainty is as great as or greater than system sensitivity. This uncertainty is derived from:

- Climate system complexity limiting our ability to model climate (Knutti 2008; Rial et al. 2004).
- Uncertainty in future human forcings on climate such as those determined for various future demographic, economic, and political scenarios (as illustrated by the breadth of possible societal futures in Forster et al. (2007)).
- Limited inclusion of the full complement of human forcings in most climate model experiments (which usually emphasize greenhouse-gas and aerosol forcing) (National Research Council 2005; Pielke 2005, 2008).

Climate model experiments, nonetheless, convey a fundamental lesson: climate system sensitivity to a host of current and potential future anthropogenic forcings is of a magnitude and rate to raise the prospect for substantial ecological impacts with consequences for the conservation of biodiversity. While we cannot with any certainty anticipate geographic details regarding the sign or size of these effects, the very character of regional climates may likely be altered over the next decades in some generalizable but crucial ways. These entail:

- Multivariate change – including in, but not restricted to, surface temperature and precipitation. Cloud cover (and light regime), wind regime, and other parameters would be expected to change concurrent with temperature and precipitation; however, regional correlations among these variables might not hold as climate patterns shift. Minimum and maximum temperatures would also likely show different responses, as they are partly controlled by different night and daytime processes.
- Changes over a spectrum of ecological timescales – that is, changes not only in annual means but also in extremes, seasonality, and interannual variability, such as those associated with El Niño-Southern Oscillation (ENSO; Meehl et al. 2007).
- Changes shifting over time – for example, trends are not likely to be monotonic if circulation patterns shift in and out of a region or if the climate system passes thresholds or potentially irreversible 'tipping points' (Overpeck and Webb 2000; Schellnhuber 2009).

These plausible changes are of a magnitude and nature to jeopardize the persistence of species, structure of biological communities and food webs, and functioning of ecosystems (Fischlin et al. 2007; Kundzewicz et al. 2007).

4.15.2.1.3 *Novel Climates*

Changes in so many aspects of climate suggest the possible formation of novel climates, that is, climates with combinations of conditions with no current analog (Williams and Jackson 2007). The prospect that current environmental niches would disappear and new reconfigured ones arise places a caveat on our reliance on previously observed relationships of climatic controls over species and ecosystem dynamics. This outlook challenges us to contemplate future states beyond those experienced or expected, including less probable but still plausible futures (Peterson et al. 2003; Turner et al. 2003).

4.15.2.2 Climatic Vulnerability of the Physical Environment

In addition to direct effects of climate on organisms, changes in climatic conditions could modify physical components of aquatic and terrestrial environments, with indirect consequences for species and ecosystems (Figure 1, upper left panel). Changing regional and local climates could alter landforms, drainage patterns, soil development, physical and chemical attributes of aquatic systems, and physical disturbance regimes – rearranging or opening up new habitats. Key geophysical processes include:

- Modified surface-water and groundwater hydrology. In winter-snow environments, for example, reduced snowpack and earlier spring snowmelt from warming can result in seasonal shifts in riverine hydrographs (Stewart et al. 2005), affecting biologically important river, wetland, and lake conditions (e.g., water level, temperature, nutrient and sediment load, and dissolved oxygen) (Poiani and Johnson 1991; Strayer and Dudgeon 2010).
- Shifting atmospheric circulation patterns – altering ocean and lake circulation, sea ice flows, and aeolian transport (of nutrients, propagules, etc). Ocean and lake circulation changes can in turn modify the horizontal distribution of plankton (including larvae) and, coupled with altered surface heat fluxes (e.g., from warmer air temperatures), affect thermal stratification and vertical mixing of nutrients. Such horizontal and vertical structural shifts have the potential to alter marine and lacustrine food webs (Brander 2007; Harley et al. 2006).
- Altered geomorphology – from climate-forced catastrophic and cumulative processes. The former include slope instability and flooding arising, for example, from increases in

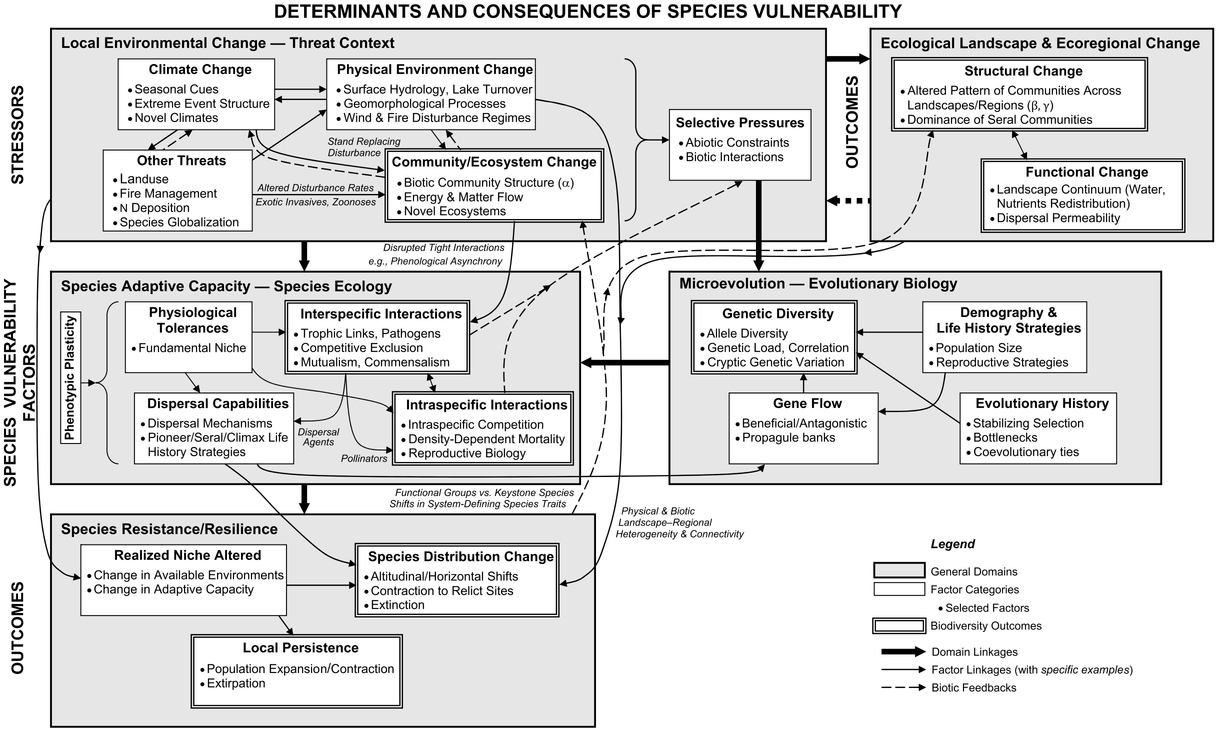
DETERMINANTS AND CONSEQUENCES OF SPECIES VULNERABILITY
STRESSORS
SPECIES VULNERABILITY FACTORS
OUTCOMES
Local Environmental Change — Threat Context
Climate Change
• Seasonal Cues
• Extreme Event Structure
• Novel Climates
Physical Environment Change
• Surface Hydrology, Lake Turnover
• Geomorphological Processes
• Wind & Fire Disturbance Regimes
Other Threats
• Landuse
• Fire Management
• N Deposition
• Species Globalization
Stand Replacing Disturbance
Altered Disturbance Rates
Exotic Invasives, Zoonoses
Community/Ecosystem Change
• Biotic Community Structure (α)
• Energy & Matter Flow
• Novel Ecosystems
Selective Pressures
• Abiotic Constraints
• Biotic Interactions
OUTCOMES
Ecological Landscape & Ecoregional Change
Structural Change
• Altered Pattern of Communities Across Landscapes/Regions (β, γ)
• Dominance of Seral Communities
Functional Change
• Landscape Continuum (Water, Nutrients Redistribution)
• Dispersal Permeability
Disrupted Tight Interactions
e.g., Phenological Asynchrony
Species Adaptive Capacity — Species Ecology
Phenotypic Plasticity
Physiological Tolerances
• Fundamental Niche
Interspecific Interactions
• Trophic Links, Pathogens
• Competitive Exclusion
• Mutualism, Commensalism
Dispersal Capabilities
• Dispersal Mechanisms
• Pioneer/Seral/Climax Life History Strategies
Dispersal Agents
Pollinators
Intraspecific Interactions
• Intraspecific Competition
• Density-Dependent Mortality
• Reproductive Biology
Microevolution — Evolutionary Biology
Genetic Diversity
• Allele Diversity
• Genetic Load, Correlation
• Cryptic Genetic Variation
Demography & Life History Strategies
• Population Size
• Reproductive Strategies
Gene Flow
• Beneficial/Antagonistic
• Propagule banks
Evolutionary History
• Stabilizing Selection
• Bottlenecks
• Coevolutionary ties
Functional Groups vs. Keystone Species
Shifts in System-Defining Species Traits
Physical & Biotic Landscape–Regional Heterogeneity & Connectivity
Species Resistance/Resilience
Realized Niche Altered
• Change in Available Environments
• Change in Adaptive Capacity
Species Distribution Change
• Altitudinal/Horizontal Shifts
• Contraction to Relict Sites
• Extinction
Local Persistence
• Population Expansion/Contraction
• Extirpation
Legend
General Domains
Factor Categories
• Selected Factors
Biodiversity Outcomes
Domain Linkages
Factor Linkages (with *specific examples*)
Biotic Feedbacks

Figure 1 Determinants and consequences of species vulnerability. The figure is broadly organized into domains of stressors (climate and other anthropogenic environmental changes, *top left panel*), species-level vulnerability factors (which limit or support a species' adaptive capacity, *middle panels*), and outcomes. Factors that set a species' vulnerability are its current adaptive capacity (*middle left panel*) and microevolutionary shifts in this capacity (*middle right panel*). Outcomes of these vulnerabilities include species persistence and range changes (*bottom panel*), altered landscape and regional ecological heterogeneity (*top right panel*), and changes to genetic diversity, community structure, and the complexity of ecosystem interactions – all of which are elements of biodiversity (double-bordered boxes). Selected factors (bulleted items) give examples for factor categories, and factor linkages and feedbacks (narrow-lined arrows) illustrate interactions; not all possible factors and linkages are shown. With respect to local and regional/landscape community structure, symbols α, β, and γ refer to Whittaker's (1960) levels of species diversity, where $\alpha =$ site (sample) species diversity, $\gamma =$ regional total diversity, and $\beta =$ among-sample heterogeneity in species diversity across the region.

storm frequency and intensity or from rapid deglaciation due to warming – with effects on upland and channel or shore geomorphology (Evans and Clague 1994; National Research Council 2010). Cumulative processes include water and aeolian erosion and deposition, whose changes result in shifting landscape patterns of aggrading and degrading soils and sediments – altering drainage networks, soil structure (creating Entisols and buried horizons, for example), and water quality (e.g., from high sediment loads) (National Research Council 2010; Soil and Water Conservation Society 2003).

- A shift in ice-dominated environments to a net thaw regime. Periglacial landscapes are an example of geomorphological surfaces that are highly sensitive to climate. As complexes of thermokarst terrain with permafrost soils and thaw lakes, these landforms exhibit both stabilizing and destabilizing interactions under increasing temperatures. Their fate depends on positive and negative feedbacks among (1) temperature change, (2) changing snowpack and vegetation (and their interaction), affecting their insulation of the soil surface, (3) soil erodibility, and (4) drainage (Kittel et al. 2011b; van Cleve et al. 1991). With respect to drainage, for example, slope inclination largely determines whether permafrost degradation under warming results in an expansion of wetlands and thaw lakes (from ground subsidence on low slopes) or in wetland loss and drying soils (from drainage on steeper slopes no longer impeded by impermeable permafrost) (Rouse et al. 1997). In glacial environments, increased melting of glacial ice with warming alters downstream chemistry, such as through enhanced weathering rates due to increased meltwater contact with subglacial rock and, with receding glacial cover, altered microbial (biogeochemical) processes in newly exposed sediments (Baron et al. 2009).
- Other climate-dependent physical disturbance mechanisms – such as changes in frequency and intensity of forest windthrow and 'fire-climate' conditions leading to wildland fires, affecting ecological disturbance regimes (O'Donnell et al. 2011; Schlyter et al. 2006).

Such physical perturbations may force wholesale changes to biotic communities and their landscape patterns (Figure 1, upper panels), facilitating rapid shifts in communities that might otherwise persist under changing local and regional climates.

4.15.2.3 Future Outlooks: Biotic Consequences

We can take key lessons about biodiversity's vulnerability to plausible future climate changes from field, laboratory, remote sensing, and modeling studies (Botkin et al. 2007; Chapin et al. 2000; Rosenzweig et al. 2007; Walther 2010). As with climate outlooks, we cannot foresee the details – timing, distribution, or nature – of future ecological outcomes with any certainty. This uncertainty similarly arises from (1) ecological system complexity limiting predictability, (2) uncertainty in future climatic forcing and feedbacks, and (3) limited accounting for synergisms with other environmental stressors in climate impact assessments.

Nonetheless, in the context of generalizations about near-future regional climates previously presented (see Section 2.01.2 and Section 2.01.3 Vulnerabilities), we can derive similar generalizations from observations and models about how biodiversity might be altered over the next decades. In broad but significant ways, these include the following:

- Shifting geographic ranges of marine, continental-water, and terrestrial species (Harley et al. 2006).
- Altered species phenologies (Root et al. 2005; Wolkovich et al. 2012).
- Species interactions spatially and temporally out of phase – altering food webs, competitive interactions, and mutual associations (e.g., pollination) (Both et al. 2009; Jha et al. 2013).
- Changing community structure – potentially giving rise to novel ecosystem types (Overpeck et al. 1992; Seastedt et al. 2008; Urban et al. 2012).
- Changes in ecosystem function – altering biophysical and biogeochemical processes, including primary production (Nemani 2003).
- Disruption of ecosystem services – affecting societal use of resources as water, food, etc. (Cardinale et al. 2012; Chan et al. 2011; Fischlin et al. 2007).

Temporal behavior of these ecological responses will generally follow not only from climatic (and other) forcing, but also from internal stabilizing or nonequilibrium dynamics. The result being:

- A new equilibrium, inasmuch as such has existed historically, would be long in coming, pending first climatic and then ecological stabilization (e.g., at centennial scales) – resulting in extended periods dominated by seral stages.
- Following from shifting climate regimes, ecological changes would not be monotonic – with no single specific outcome developing and persisting over the long term (e.g., no 'winner' or 'loser' species).
- Internal dynamics would exhibit system lags, regime shifts, and tipping points (Allen and Holling 2010; Biggs et al. 2009; Jones et al. 2009; Metzger et al. 2009).

These potential outcomes arise from the fundamental nature of biodiversity and its climatic vulnerability. Processes and factors controlling this vulnerability are explored next.

4.15.3 Nature of Biotic Vulnerability

4.15.3.1 Vulnerability across the Biodiversity Hierarchy

Biodiversity broadly includes complexity across levels of biotic organization from genetics and populations to communities, landscapes, and ecoregions (and so on). Within these levels, biodiversity also includes complexity with respect to composition (elements present), structure (arrangement of elements), and function (interactions among elements) (Noss 1990). The structure and function of genetic through ecoregional diversity contribute to the maintenance of species diversity and are themselves established as important conservation goals (Groves et al. 2002). Biodiversity is vulnerable to climate across this hierarchy in complex and highly interactive ways (Fischlin et al. 2007; Walther et al. 2002). This section starts with a species-level approach to climate vulnerability, focusing on a species' adaptive capacity and its links to genetic diversity, and then discusses community and ecosystem vulnerability, landscape connectivity, and synergisms with other threats.

4.15.3.2 Species Adaptive Capacity

4.15.3.2.1 Species Ecology

Physiological Range

A species' adaptive capacity – that is, the potential for resistance and resilience to environmental change – arises from flexibility in its ecological relationships (**Figure 1**, middle left panel). On first consideration, such flexibility with respect to climate is tied to the breadth and shape of physiological response curves – such as with respect to interacting thermal, moisture, light, chemical (nutrients, salinity), and other climate-linked environmental conditions. Broad physiological optima will support species resistance; while species with narrow physiological limits are subject to catastrophic responses (e.g., tropical organisms with little freeze tolerance). (The genetics of broad versus narrow climatic optima is discussed later on.) In addition, physiological tolerances change with life stage in many species (Harley et al. 2006), so that vulnerability may be linked to a critical time or may shift among factors during an organism's lifespan.

Species Interactions

The link between a species' adaptive capacity and physiology may, however, be muddled by interactions with associated species, including competitors, predators, prey, mutualists, and pathogens (**Figure 1**). Consequently, species vulnerability may be just as much indirectly determined via climate responses of associates (and so by altered community compositional and structural diversity) as by direct forcing of a changing climate. The impact of community restructuring (discussed later) on a species' vulnerability propagates in through trophic and other ecological networks – that is, from beyond the species' most immediate connections. Altered interspecific interactions can ameliorate a species' vulnerability, such as through competitive release, or exacerbate it as from reduced resource availability. Species with high adaptive capacity:

- Can readily shift resource utilization under shifting competitive and trophic environments.
- Are not highly dependent on mutualistic relationships (or at least not with species lacking matched adaptive capacity) (Hughes et al. 2003; Jha et al. 2012).
- Have resistance (expressed or latent) to emergent diseases.

Population Viability

Population dynamics also determine species vulnerability (**Figure 1**). Direct climatic impacts on reproduction and mortality rates alter population viability across a range of timescales (e.g., from hourly events to decadal variability). Such controls over population size are manifested as both density-independent climate effects (as from catastrophic events) and density-dependent effects (where the climate impact depends on, for example, the magnitude of intraspecific competition for food, shelter, and mates). At weekly scales, for example, changes in frequency and timing of severe winter storms can have both density-independent and dependent effects on large mammal survivorship (Berger 1983; Hallett et al. 2004).

Both animals and plants exhibit climate-induced shifts in reproductive traits affecting population dynamics, such as fecundity, generation time, breeding/flowering season, and other phenological traits (Inouye 2008; Isaac 2009; Post et al. 2001). How traits respond to climate and the consequences for population viability depend on a species' overall life-history strategy – such as for r- versus K-selected species, generalists versus specialists, and for different mating systems; in these contrasts, similar climatic behavior can generate opposite outcomes (Isaac 2009).

Population viability is also tied to species interactions, as those discussed above. At seasonal scales, reproduction and survivorship are altered by loss of phenological synchrony between:

- A species' climate-cued life-history events and climate-cued trophic resource availability, as seen in migratory and winter-dormant vertebrates (Both et al. 2009; Forchhammer and Post 2004; Harrington et al. 1999; Inouye et al. 2000).
- The climate-cued life-history events of mutualists, as for plants and their pollinators (Jha et al. 2012).

At interannual and longer scales, climate affects predator-prey population cycles – such as that involving Canadian lynx and snowshoe hare (Stenseth 2007) – and climate-regulated host-disease dynamics, as in insect herbivore-parasitoid systems (Hance et al. 2007; Stireman et al. 2005) and plant host–pathogen interactions (Brasier and Scott 1994; Woods et al. 2005).

The constraints imposed on adaptive capacity by intra- and interspecific interactions tend to narrow a species' range relative to its potential climatic limits based on physiology alone. If changing population and community dynamics shift these constraints, a species may reveal latent capacity to fill niches that are consistent with its physiological limits but from where it has been excluded.

4.15.3.2.2 Dispersal Capacity and Range Shifts

Vulnerability also depends on a species' ability to disperse away from sites becoming less favorable to improving ones – that is, to successfully track suitable conditions as they shift across a landscape or region (**Figure 1**, middle left panel). While the potential for species range shifts is often evaluated with empirical 'climate envelop' or environmental niche models, dispersal success is tied to dispersal life-history strategies and interspecific interactions generally not incorporated in these models (Davis et al. 1998; Wiens et al. 2009; however, see Anderson et al. 2002 and Keith et al. 2008).

Even within taxonomic groups, species substantially differ in dispersal attributes, setting their potential for keeping up with elevational or lateral shifts in climates (Chen et al. 2011; Urban et al. 2012). Species factors include the following:

- Capacity for diffusive or jump dispersal, whether by self-locomotion or facilitation by wind, water, or other species.
- Establishment life-history strategies (e.g., reproductive rates, competitive abilities, and adult survivorship associated with early versus late successional species).

Successful dispersal is also a function of environmental conditions along the way. Source-to-sink abiotic and biotic site factors include the following:

- A species' current distribution and population size (source strength) including persistent relict populations existing outside of its generalized climatic range (Botkin et al. 2007).
- Landscapes en route presenting physiographic or biotic barriers and corridors (including limitations or opportunities offered by human-modified domains).

- Suitability of potential sink habitats in terms of their abiotic, trophic (food resources, predator), and competitive setting (Urban et al. 2012).

Species whose in situ adaptive capacity is low – and thus vulnerable to local extirpation – and additionally are poor dispersers and isolated from emerging favorable sites by physiography or human land use are additionally vulnerable to extinction (**Figure 1**, bottom left panel). While these processes look at the leading edge of range shifts, demographic factors and reproductive traits (e.g., longevity, cloning) and disturbance tolerance are species-specific controls over lags (species persistence) at the trailing edge (Elliott-Fisk 1983; Hampe and Petit 2005).

Species differences in adaptive capacity in general and dispersal ability in particular would lead to differential rates of range movement under a shifting climate (and disturbance) regime. A resulting mixture of colonizing, lagging, and declining species will contribute to community structural disruption, the predominance of seral (successional) associations, and, potentially, to the rise of novel communities (**Figure 1**) (Urban et al. 2012; Williams and Jackson 2007). The nature and rate of community change will depend on:

- Relative 'openness' of the current community – versus one presenting a highly competitive environment.
- Climate vulnerability – and hence degree of persistence – of dominant and keystone species that maintain existing community structure.
- State-changing disturbance (fire, insect outbreaks).
- Dispersal and establishment abilities of arriving species.

Under slow rates of climatic change, communities may maintain their composition but alter their relative structure, at least in the shorter term (Breshears et al. 2008; Kelly and Goulden 2008). However, under high disturbance with rapid changes in local climate, communities may collapse, presenting open environments to arriving species. Community structural vulnerability is discussed further in Section 3.03.1 Introduction.

4.15.3.2.3 Phenotypic Plasticity

Phenotypic plasticity can shift adaptive capacity under a rapidly changing climate without relying on genetic variation (Reed et al. 2011; Rice and Emery 2003). Requirements for adaptive phenotypic plasticity are that:

- environmental cues are sufficiently reliable to trigger plastic responses,
- plastic responses sufficiently track the pace and breadth of environmental changes,
- fitness benefits exceed costs of maintaining plastic potential (Reed et al. 2011).

The degree of plasticity varies widely among taxa. For some species, adaptive plasticity is not sufficient to optimize fitness throughout a species' current climatic range (e.g., as seen for a temperate-grassland annual forb in a reciprocal transplant study, Etterson 2004b), potentially leading to reduced local population viability under a shifting climate. For others, it may be as great as to accommodate wide climatic shifts. For example, over the Pleistocene glacial–interglacial cycle, a kangaroo rat species largely maintained its current distribution by shifting its realized niche likely through phenotypic plasticity, rather than with genetic change (Jezkova et al. 2011).

4.15.3.2.4 Geographic Gradients in Adaptive Capacity

Genetic Differentiation Across a Species' Range

As the underlying basis for adaptive capacity, genetic make-up sets the vulnerability of a species to a changing environment. However, abiotic and biotic constraints on populations tend to affect a species' adaptive capacity differently at range extremes and at extremes versus in its core, applying different selective pressures and driving geographic genetic differentiation (Bentz et al. 2001; Case and Taper 2000; Davis et al. 2005; Hampe and Petit 2005; Howe et al. 2003). Consequently, physiology, life history, and other (genetic-based) elements of adaptive capacity may differ substantially for populations at the core of a species' distribution versus those at its limits. Such populations may then have different responses to similar climatic change. A species' vulnerability then varies geographically not only with varying availability of suitable habitats, but also with location-specific genetically determined capacity to adjust to new local niches (e.g., Etterson 2004a; Rehfeldt et al. 1999).

A consequence of this geography is that populations in the core of a species' range may be maladapted to its marginal climates. Such a 'core population' may not be viable under a climate shift that brings it near to, but still within, the limits of the species' current climate range. Under these conditions, empirical niche (climate envelop) models would overestimate a species' persistence.

Role of the Past

Biogeographic history (how species got to where they are now) and evolutionary history (how they changed along the way and once there) are determinants of current genetic geography. Regional climatic history plays a role in such geographic differentiation. For example, it can act to reduce local genetic diversity under diametric conditions of:

- steady climate regimes, through stabilizing selection (Rice and Emery 2003),
- rapid climate change or severe events (such as sustained drought), creating genetic bottlenecks.

In both of these cases, past conditions potentially reduce current adaptive capacity and increase local vulnerability to future climate shifts. Effects of climatic variability on genetics are discussed further in the next section.

4.15.3.2.5 Shifting Adaptive Capacity in Time: Microevolution

Direct abiotic and indirect biotic forcing associated with a changing climate apply corresponding selective pressures; the question is whether these pressures can sufficiently shift population genetics at ecological timescales to reduce species vulnerability. Microevolution, that is, evolutionary change within a species or its populations, has allowed some taxa to adapt to recent human-forced environmental change, including altered climatic conditions (reviewed in Rice and Emery 2003). This is to say that genetic shifts in populations that maintain their viability can occur at rates matching rapid environmental change. Consequently, evolutionary rates may be large enough for some species to adapt to rapidly changing local climates, reducing the probability of their extinction (Reed et al. 2011; Rice and Emery 2003).

Climatic Selective Pressures

Climate-linked selective pressure produces three generalized outcomes as a function of climatic temporal behavior (Reed et al. 2011; Rice and Emery 2003):

- Climatic consistency gives rise to stabilizing selection reducing generic diversity, in turn reducing adaptive capacity, as previously mentioned.
- Directional change in climatic conditions supports net directional selection, shifting adaptive capacity. However, rapid climate shifts exert strong selective pressure, which may exceed microevolutionary potential (discussed shortly). A consequence of strong selection is high levels of mortality. This may make even currently robust populations vulnerable by diminishing their size and condition to levels where they become subject to stochastic fluctuations in numbers and genetics (genetic drift) (Reed et al. 2011). This threat to population viability may occur even as directional selection is moving phenotypes to a new environmental optimum in the remaining population.
- If climatic variability increases in a way that gives inconsistent direction to selection pressures, it can disrupt both stabilizing and directional selection. This would lead to poor climatic optimization and reduced adaptive capacity. Alternatively, increased variability can promote selection for phenotypic plasticity, but only if the altered climate regime has a predictable element that be relied on as an environmental cue – a required condition for plasticity noted earlier. Without this predictability, however, plasticity would be less reliable and so less favored under increased climate variability (Reed et al. 2011).

Strong environmental perturbation can, in addition, trigger release of cryptic genetic variation – variation present but otherwise not phenotypically expressed (Gibson and Dworkin 2004; McGuigan and Sgrò 2009). Such a release produces novel, potentially adaptive phenotypes (Hayden et al. 2011). Suggested trigger mechanisms are through environmental disruption or genetic mutation (which itself can be induced by environmental stress, Reed et al. 2011).

Factors Controlling Microevolution

Microevolution is limited by (1) genetics, (2), reproductive biology and demographics, and (3) coevolutionary processes (Rice and Emery 2003). Genetic factors that constrain or facilitate microevolution include the following:

- Local genetic diversity, providing either a genetic source for adaptive shifts or a drag from genetic load (suboptimal genes reducing fitness).
- Metapopulation gene flow, which can provide a population with either (1) genotypes well adapted to new conditions or (2) maladapted genes more suited to the source location and so adding genetic load (i.e., antagonistic gene flow).
- Phenotypic plasticity, discussed earlier, which can buffer the negative effects of strong selective pressure and allow time for genotypes to track environmental shifts.
- Positive or negative genetic correlation among adaptive traits (which each support an optimal phenotypic response to an environmental change) can accelerate or hinder selection relative to traits that act independently. Traits that act in concert (through synergistic genetic interaction) promote adaptive change. On the other hand, with negatively correlated traits, promotion of one trait reduces selection for the other. Such antagonistic genetic interaction makes directional selection ineffective in optimizing a phenotype to a consistently changing environment (Etterson and Shaw 2001). Genetic interactions are further complicated when traits that are positively correlated under selection favoring some phenotypes are negatively correlated in selection favoring others (Snitkin and Segrè 2011).

On this last topic, positive genetic correlations may not be stable under multivariate environmental change, where selective pressure is for phenotypes to track multiple shifting optima (Reed et al. 2011). Additionally, under the development of shifting or novel climates, a breakdown of currently reliable correlations among environmental variables (such as between temperature and day-length seasonality) may disrupt current positive genetic correlations (such as among traits setting cold-season acclimation in temperate and boreal plants; Howe et al. 2003).

Microevolutionary factors related to reproductive biology and demography include the following:

- Environmentally cued shifts in sexual versus asexual reproduction in plant, animal, and microbial taxa (Chen and McDonald 1996; Elliott-Fisk 1983; Hughes et al. 2003).
- Generation time, fecundity, and population size – where short generations, many offspring per generation, and large populations contribute to higher population growth potential, facilitating adaptive evolutionary shifts (Hughes et al. 2003; Reed et al. 2011).
- Reproductive longevity of adults and viability of dormant propagule reservoirs (e.g., seed banks), which can provide either genotypes that have come around again to be well adapted or ones that increase genetic load (Hughes et al. 2003; Rice and Emery 2003).

Coevolutionary selective pressures arise from shifting trophic, mutualistic, or epidemiologic interactions. These pressures may be particularly crucial when one species' microevolutionary response is tightly constrained by the adaptive capacity of and concurrent (but not necessarily matching) evolutionary changes in coevolved associates (Holt 1990; Rice and Emery 2003).

4.15.3.3 Vulnerability of Community Structure and Ecosystem Function

4.15.3.3.1 Structure

Response of communities to a changing environment is determined not only by species' individual responses to external forcing, but also by internal dynamics. Community structural changes (composition, richness, evenness) arise from the relative strengths of forcing and species interactions. Three paths are determined by the dominance of (1) physically disruptive climate forcing, (2) weak biotic interactions, or (3) strong, system-defining biotic interactions (Figure 1, upper left panel).

In the first case, climate drives catastrophic or cumulative changes to the physical environment sufficient to disrupt the integrity of a community (as previously discussed). Primary or secondary succession will give rise to potentially novel sequences of communities under new, shifting abiotic (climate, disturbance regime) and biotic (e.g., arriving species) conditions.

Under a climate that is not so disruptive to the physical habitat, community responses to climate depend on the strength of interactions among species (Chapin et al. 2000). In communities where species belong to fairly generic functional groups and interactions are weak (that is, flexible among roughly substitutable species), community structure is affected by an overall shifting presence and abundance of species as they respond to climate and to trophic, mutualistic, and competitive interactions. In this case, communities adjust primarily 'bottom up' – progressing up trophic networks in response to, for example, changes in primary producer or microbial decomposer populations, the principal facilitators of system energy or nutrient flows (Chapin et al. 2000; Harrington et al. 1999; Inouye 2008; Mantua et al. 1997; McGowan 1998; Walther 2010).

In communities with strong interactions, on the other hand, structural changes may be determined by the presence and abundance of single species – such as for keystone taxa, whose presence or loss cascades 'top down' through trophic levels (Chapin et al. 2000; Power et al. 1996; Walther 2010). In general, such species-sensitive restructuring occurs where:

- Mutualistic, trophic, or competitive interactions are tight – e.g., for animal pollinator–plant interactions, top predators, and grazer-determined plant succession (Collins and Calabrese 2012; Jha et al. 2012).
- A species' traits strongly control system dynamics – such as for species that tightly regulate system resources, disturbance regime, or microclimate (e.g., nitrogen-fixer, low water-use efficiency, fire-prone, and permafrost-stabilizing plant species) (Chapin et al. 2000; D'Antonio and Vitousek 1992; van Cleve et al. 1991; van Wilgen et al. 1996; Wilson and Agnew 1992).

Within a food web, strong bottom-up and top-down effects may both play a role – with top-down restructuring influencing lower trophic levels and bottom-up simultaneously affecting top levels (e.g., Shurin et al. 2012), potentially in a way that can synergistically contribute to ecosystem stability (de Ruiter et al. 1995).

Emergent versus Species Responses

A straightforward community-level phenological response to shifts in seasonal climate may say little about individual species responses and the consequences for tight species interactions. For example, a lengthening of the growing season for mid- and high latitude terrestrial plant communities could be expected to increase food resources for herbivores. However, this community response is likely emergent from a variety of individual plant species responses – some advancing their phenologies, some with cycles sped up or lengthened, and others with little change (Steltzer and Post 2009). For herbivores, a consequence can be disrupted timing of plant species that provide crucial dietary needs during specific periods of the summer (e.g., in preparation for hibernation) (Hill and Florant 1999; Steltzer and Post 2009).

4.15.3.3.2 Ecosystem Function

Climate and Plant Functional Types

Terrestrial biogeochemical processes are largely controlled by moisture and thermal regimes in interaction with soil properties (e.g., water and nutrient holding capacity), vegetation, and geomorphology (e.g., hillslope position) (Band et al. 1993; Daly et al. 2000; Parton et al. 1995). The role of plant community structure and species composition can be generalized by plant functional types that categorize species' contributions to ecosystem physiology and architecture (Smith et al. 1997). Such functional distinctions affect biogeochemical rates through quantity and quality (nutrient versus structural content) of plant matter inputs inherent in contrasts of, for example, annual versus perennial herbaceous, deciduous versus evergreen woody, C_4 versus C_3 photosynthetic pathway, and nitrogen fixing versus non-fixing species. Climate-driven shifts in the diversity of an ecosystem's plant functional types, especially with the gain or loss of key types controlling system dynamics, can be major determinants of the climate response of energy and matter flow rates and pathways (Díaz and Cabido 2001; Kappelle et al. 1999). This sensitivity to shifts in key types can occur even if each type is represented by only one to a few species, resulting in little change in overall species diversity.

Aboveground–Belowground Ecosystem Interactions

Material and energy flows in terrestrial ecosystems are also determined by climate-sensitive interactions between above- and belowground realms and so by traits of these communities (Bardgett et al. 2005; Wall 2007; Wardle et al. 2004). Belowground microbial and faunal communities interact with the aboveground realm in ways that depend on the nature of their association with plants – those in food webs associated with roots (with primary consumption by root herbivores, parasites, and pathogens), in detrital food webs (decomposers), versus in mutualistic association with roots (mycorrhizae) (Bever et al. 2010; De Deyn and Van der Putten 2005; Wardle et al. 2004).

The aboveground community exerts strong control over detrital and root food webs primarily through the quantity and quality of plant matter – a function of plant community composition, as described above. In addition, aboveground herbivory can alter plant tissue quality – in the short term, through plant biochemical responses (of increased nitrogen content and/or secondary defensive compounds) and, in the long term, through plant community shifts (to lower quality forage species) (Wardle et al. 2004).

At the same time, belowground communities strongly influence plant productivity (and tissue quality) through:

- The detrital food web, both mineralizing organic inputs to available forms and competing with plants for these nutrients.
- Mycorrhizal facilitation of plant nutrient uptake.
- Degradation of root uptake efficiency by the root-associated food web (through root consumption and disease).
- Belowground microbial and invertebrate induction of plant defenses against aboveground herbivory and plant-shoot pathogens, altering plant growth and chemistry (defensive compounds). Such plant productivity and tissue chemical responses can be both plant- and belowground inducer-species specific and have bottom-up community effects, shifting plant competitive and trophic interactions (Bezemer and van Dam 2005).

Climatic vulnerability of ecosystems emerges from the compositional and functional diversity of these communities and complexity of their interactions (Chapin et al. 2000; Kappelle et al. 1999; Wardle et al. 2004). Biogeochemical processes and functional group behavior are strongly sensitive to their climatic controls; however, ecosystem model intercomparison studies suggest high uncertainty in our understanding of this vulnerability even at the broadest (regional and continental) scales (Cramer et al. 2001; Purves and Pacala 2008; Schimel et al. 2000). At finer scales, the magnitude and expression of climate vulnerability are even less predictable because above- and belowground dynamics are highly nonlinear and depend on site details, such as soil fertility and, as just described, soil and plant community composition and aboveground herbivory (Wardle et al. 2004). Such nonlinear ecological networks are potentially capable of sudden regime shifts and passing through tipping points in their structure and function (Biggs et al. 2009; Hastings and Wysham 2010; Wall 2007).

4.15.3.4 Landscape–Global Continuum

The spatial arrangement of communities and ecosystem processes on the landscape brings additional complexity arising from physical and biotic connectivity. Connectivity of landscape units provides for water- and air-mediated flow of energy and materials (e.g., organic and inorganic particles, water, and propagules) downslope and downwind (Reiners and Driese 2001; Seastedt et al. 2004; Soranno et al. 1999). In addition, landscape continuity facilitates seasonal and ontogenetic (life-stage) migrations and range expansion (Berger 2004; Olds et al. 2012). Such biogeochemical, population, and other linkages are vulnerable to disruption of the physical environment (e.g., shifted hydrology and destabilized landforms, as discussed earlier) and interruption of biotic continuity through rearrangement or loss of crucial communities (such as suitable habitats forming corridors or those that are key sources for transported organic material).

Connectivity extends to regional and global scales with interbasin, intercontinental, and between ocean and continent aeolian transport of aerosols (e.g., nitrogen deposition), dust (from aridlands), and organisms (e.g., microbes, insects, propagules) (Baron et al. 2009; Brander 2007; Sharma et al. 2007; Washington et al. 2009; White et al. 2012). Sustained changes in such inputs can alter ecosystem function and structure (Avila and Peñuelas 1999; Fenn et al. 2003; Steltzer et al. 2009).

4.15.3.5 Synergisms among Climate and Other Stressors

Climatic impacts on species adaptive capacity are, in addition, in the context of other environmental stressors on biodiversity (Figure 1, upper left panel). These include direct anthropogenic effects such as habitat conversion (e.g., Vieira et al. 2009), exotic invasive introductions ('biotic homogenization,' Olden et al. 2004), and disruption of biogeochemical cycles (Vitousek et al. 1997). Acting together, these stressors exhibit not only additive effects but also strong synergisms with climate (Brook et al. 2008). Exacerbating feedbacks between climate and other stressors include those with:

- Habitat modification – including (1) atmosphere-land surface feedbacks accompanying land use change, such as fragmentation, salinization, and desertification (e.g., accelerated drought with deforestation; Laurance and Williamson 2001) and (2), for aquatic environments, compounding influences of precipitation regime change, upland land use, and water impoundment on light, temperature, sediment load, and chemistry of continental and coastal waters (Walling 2009).
- Overexploitation of species utilized for food, timber, etc. where reduction or extirpation of populations and disruption of food web dynamics increase a species' vulnerability to other stressors (such as climate) (Biggs et al. 2009; Brander 2007; Nellemann et al. 2008).
- Altered fire disturbance regime – from environmental changes including (1) human-related fire suppression or ignition, (2) shifts to more fire-prone plant communities with the establishment of invasive exotics, and (3) fertilization from atmospheric nitrogen deposition adding fuel load (D'Antonio and Vitousek 1992; Fenn et al. 2003; Schoennagel et al. 2004).
- Altered chemical environment – inducing biogeochemical and community changes from (1) elevated atmospheric CO_2-induced fertilization (of terrestrial plants) and ocean acidification (to the detriment of calcifying marine organisms), (2) introduced toxins via air, soil, and water pollution, (3) atmospheric deposition causing soil and water acidification and enhancing nitrogen inputs (as just noted regarding fire), and (4) altered terrestrial nutrient runoff to continental waters and oceans (Baron et al. 2009; Brander 2007; Fenn et al. 2003; Gitay et al. 2001; Kleypas et al. 1999; Pandolfi et al. 2011). In terrestrial and aquatic systems, changes in physical climate influence these chemical deposition, infiltration, and runoff impacts (1) directly through shifting precipitation and snowmelt regimes and (2) synergistically, with thermal and moisture regimes also affecting these biogeochemical responses.
- Insect outbreaks – aided by climate directly through (1) altered host plant susceptibility (e.g., plant moisture status) and (2) altered insect life cycles (e.g., a step-up in the number of breeding cycles per annum) (Mitton and Ferrenberg 2012; Raffa et al. 2008).
- Invasive exotics – with climate-facilitated spread of invasives through, for example, new establishment opportunities arising from shifts in (1) dispersal routes (via wind and water circulation), (2) disturbance regimes, or (3) competitive setting (from community shifts) (Burgiel and Muir 2010; Hellmann et al. 2008). In a climatic feedback, the impact of invasives on community structure can be strong enough to alter basin microclimates and hydrology (van Wilgen et al. 1996).
- Disease invasion – where the introduction and spread of emergent diseases into wildland plant and animal communities are driven by an array of factors acting individually and synergistically. These include: (1) land use change encroaching on natural areas, such as land conversion for agriculture, settlement, and water impoundment (giving rise, for example, to zoonoses – animal diseases transmitted through contact of wildlife with domestic animals and humans; Patz et al. 2000), (2) atmospheric N deposition and elevated atmospheric CO_2 (e.g., affecting susceptibility to disease due to altered plant growth patterns; Mitchell et al. 2003), (3) diminished plant community diversity resulting in increased host-species

densities (e.g., directly through management or indirectly through plant preferences of introduced grazers; Borer et al. 2009), and (4) changing climatic conditions (Crowl et al. 2008; Patz et al. 2000; Woods et al. 2005). Introduction of new diseases and elevated infection rates significantly impact the structure and function of ecosystems (Anderson and May 1986; Crowl et al. 2008), with the outcome determined in interaction with climate and other stressors.

Such a multiple-stressor context provides for a more encompassing assessment of climate vulnerability, yet with concomitant levels of added uncertainty (Sala et al. 2000).

4.15.4 Implications for Biodiversity Conservation: Fundamentals, Uncertainties, and Planning

4.15.4.1 Fundamentals of Vulnerability

Fundamental lessons that emerge regarding the vulnerability of biodiversity to climate are:

- Biodiversity at species through landscape levels is vulnerable to climate acting (1) directly on organisms – which, through ecological networks, generate and are subject to higher-order population, community, and ecosystem vulnerabilities, (2) indirectly through climatic alteration of the physical environment, and (3) synergistically with other stressors.
- At the species level, adaptive capacity – countering such vulnerability – arises from (1) physiological breadth, (2) life-history strategies affecting population viability, (3) flexibility of interspecific (mutualistic, competitive, and trophic) interactions, and (4) dispersal capable of tracking shifting favorable conditions elevationally and laterally.
- Species adaptive capacity is mutable through (1) phenotypic plasticity and (2) microevolution – both highly variable among species as a function of genetic, reproductive, and coevolutionary controls. Some elements of adaptive capacity are latent – potentially released by changing conditions (such as release from competition and triggering of cryptic genetic variation).
- Genetic basis of adaptive capacity geographically varies over a species range as a consequence of (1) variation in microevolutionary potential, (2) abiotic and biotic environmental gradients affecting selective pressure, and (3) climatic and evolutionary history.
- Vulnerability of communities and ecosystem material and energy flows emerges from (1) community composition, especially as it relates to the functional diversity of species (i.e., in terms of general functional types and species with system-determining traits), (2) complexity and strength of interactions, especially the extent to which trophic network structure is determined by bottom-up and/or top-down interactions, and (3) matter and energy exchange among landscape units (and with domains farther afield).
- In all these aspects, vulnerability is context dependent, for example, what (what species, with what genetics, and in what community networks), where (in the core versus margin of its geographic range, and in what current climatic, physiographic, and ecological region), and when (what history, what foreseeable future threats).

4.15.4.2 Uncertainties

These vulnerabilities involve complex interactions among multiple system components and across a broad range of time and space scales. This complexity results in nonlinear dynamics, as previously noted, potentially exhibiting lagged (Jones et al. 2009; Metzger et al. 2009) and threshold (regime-shift or tipping-point) behavior (Barnosky et al. 2012; Biggs et al. 2009; Burkett et al. 2005; Malhi et al. 2009). Such systems are inherently difficult to predict (Hastings and Wysham 2010; Holt 1990; Scheffer et al. 2009; Wardle et al. 2004), affecting our ability to assess species and system vulnerability.

Given that vulnerability is judged relative to the magnitude and nature of stressors, such assessment is also hampered by uncertainty in drivers of change – whether climatic or from other threats, as previously discussed. Predictability is additionally constrained by our limited understanding of even modest portions of vulnerability dynamics summarized in the previous section (and in Figure 1) – especially when focused on a species or community of concern, much less for whole landscapes. One source for this deficiency is insufficient observations of systems under rapid, multisource environmental change that would reveal key dynamics – such as, to name but a few:

- Latent adaptive capacity of species such – as phenotypic plasticity, microevolution, and cryptic genetic variation
- Co-microevolutionary potential of mutualists (e.g., Rice and Emery 2003)
- Cross-temporal and spatial scale population responses to climate variability (e.g., Hallett et al. 2004; Stenseth and Mysterud 2005)
- Role of interspecific competition during species range movement (Davis et al. 1998)
- Threshold versus system-stabilizing community dynamics (e.g., de Ruiter et al. 1995)
- Dynamics leading to the rise of novel ecosystems (Williams and Jackson 2007).

In sum,

- Biodiversity is vulnerable to changing climate conditions across its breadth and depth – that is to say, altering composition, structure, and function of species genetics and populations and communities, ecosystems, and landscapes. Vulnerability is highly interwoven across these levels and across temporal and spatial scales, as well as being context dependent.
- Uncertainty in the outcomes of this vulnerability, however, is high—that is, potentially equal to or greater than the magnitude of the vulnerability.

The bottom line is that the task of incorporating climate vulnerability into conservation planning is both essential and inherently difficult.

4.15.4.3 Dealing with Climate Uncertainty in Conservation Planning

While plausible future changes in climate put at risk species persistence and the integrity of community networks and ecosystem function, uncertainty in how this will be played out means we are far from being able to adequately assess ‘on the ground’ outcomes of this vulnerability. Such uncertainty can be perceived as overwhelming, blocking progress toward including climate vulnerability in conservation planning. To overcome this roadblock, a strategy is needed to deal with uncertainty in an appropriate way – that is, a strategy that explores and copes with uncertainty, rather than putting it aside.

There are many areas in our professional and personal lives where we undertake strategic planning in the context of uncertain future conditions; nonetheless, we face these uncertainties and devise and implement plans according to our expertise and information available. Conservation planning by its nature deals with threats that have highly unpredictable elements such as habitat fragmentation, invasive species, or altered disturbance regime. We may not know, for example, the timing, duration, intensity, location, or other critical attributes of a threat, yet conservation teams devise management plans to address these threats (Groves 2003).

We can also look for guidance for planning under uncertainty in disciplines farther afield. Uncertainty in financial markets has similarities with that in ecological systems (Scheffer et al. 2009). In both cases, high uncertainty arises from:

- Low predictability due to system complexity – e.g., from nonlinear, positive and negative feedback, threshold, and cross-scale (micro- to macroeconomic, genetic to ecosystem) dynamics.
- Poorly understood (and poorly quantified) system-wide behavior or behavior of even limited domains (i.e., economic sectors, 'vulnerability domains' in **Figure 1**).
- Unknown, or not widely recognized, intrinsic and extrinsic threats to system stability.

We can then borrow basic tenets from financial planning for a scheme for conservation planning under an uncertain climate future. In analogy to 'to invest smart,' 'to conserve smart' is to implement strategies that recognize and handle uncertainty – that hedge against worst-case scenarios, but which do not lead to poor decisions under current conditions. I paraphrase six investment 'coping with uncertainty' tenets which contribute to an integrated conservation strategy for climate change (presented in Section 4.15.4.4). (Quoted investment lessons are not from specific sources, but, rather, are common guidance found, for example, on the Internet.)

4.15.4.3.1 Tenet 1: Monitoring and Historical Analysis

Monitoring temporal dynamics and long-term trends develops a knowledge base and intuition of system dynamics influencing biodiversity on which to base and modify decisions (analogous to "Never invest in something you don't understand"). An early emphasis on monitoring, if not already ongoing, builds an observational dataset that can be the basis for historical analyses and model development. Initiating monitoring at the onset – not after the planning process is completed nor as an afterthought to monitor a plan's effectiveness – has the benefit of providing the longest possible record. A longer observational record increases the chance of capturing dynamics counter to or more complex than our expectations (e.g., shifting or unstable behavior). Care should be taken in designing and implementing a monitoring program to assure that the record is free from inhomogeneities and other data quality issues so it may be relied on for temporal analyses (Kittel 2009).

Analysis of long-term records lends valuable insights to the question of vulnerability and with it a first-order estimate of future behavior. However, this tenet comes with a caution regarding extrapolation that future dynamics may well go outside of what has been observed in the past ("Past performance is no indication of future return").

4.15.4.3.2 Tenet 2: Diversify Holdings

A common conservation planning strategy for identifying critical locations for protective measures is to select a portfolio of best sites possible – sites with, for example, (1) the largest populations of a species or the greatest extent of an ecosystem of interest, (2) the best quality of habitat, and (3) the lowest level of threats, current or foreseeable (such as areas with substantial buffer zones – e.g., buffered from roads and other human development). These 'best of the best' criteria assist in selecting conservation sites with the most intact processes supporting biodiversity and ecological and evolutionary function.

Achieving diversity among such sites in terms of their key attributes is a complementary strategy to reduce risk to biodiversity under high environmental uncertainty ("Diversify your portfolio to reduce risk"). Selecting multiple sites under best-site criteria for multiple conservation elements (species and ecosystems) will diversify holdings as a matter of course, with sites selected to optimize criteria in different ways for different elements. However, as in investing, site diversification can adhere to yet higher standards – a diversity of sites meeting best-condition criteria may be akin to a portfolio of highly rated stock diversified across sectors; focused on stock, it has higher risk relative to one diversified with additional instruments as bonds, real estate, and commodities ("Similarity among holdings reduces a portfolio's effective diversification"). Concepts (and tools) regarding financial portfolio optimization can be employed to design and evaluate diversification in conservation plans (Ando and Hannah 2011; Moore et al. 2010).

An additional strategy to enhance diversity in site selection is to recognize opportunities to support adaptive capacity in otherwise passed-over sites. For example, low priority sites – whether an occurrence of a currently small, unviable population or a marginal habitat – may have greater value in light of climatic uncertainty if they harbor critical source populations for geographic expansion and genetic diversity or have the potential to develop into prime habitat under a more favorable climate. In addition, currently low value, degraded sites with good potential for restoration have added value if they offer an opportunity to reestablish key habitats and landscape integrity, improving species and system adaptive capacity (e.g., Johnson et al. 2005; Renton et al. 2012). This is not a strategy to select poor sites per se, but to seek value in less favorable locations.

4.15.4.3.3 Tenet 3: Multiple Planning Horizons

Biodiversity conservation planning is by definition for the long-term. However, under a changing but uncertain climate, devising a plan relevant to both current and (indeterminable) future states is problematic. A solution is to develop a multiple-goal conservation plan, where different conservation strategies are developed for different planning horizons ("Establish multiple investment strategies to meet financial goals for different time horizons"). One such multigoal approach is to separately focus on short- versus long-term climate risk, following a scenario of climate change shifting from being moderately to severely disruptive to species and ecosystems over the coming decades – a scenario consistent with fundamental lessons regarding plausible climatic change and ecological vulnerability (see Section 4.15.2, Section 4.15.4.1). These two planning horizons have their parallels elsewhere in species conservation assessment, such as in 10- and 100-year timeframes used for evaluating population reduction and extinction risk in the International Union for Conservation of Nature Red List (International Union for Conservation of Nature 2010).

Moderate Climatic Disruption Strategy

Under a multiple-time horizon approach, conservation strategies for the near-term could consider potential climatic change over, for example, the next 10–20 years to be sufficient to alter population survivorship and landscape processes – but under which species and ecosystems are still capable of local adaptation. Goals would then be to:

- Protect current and restore potentially high-value conservation sites (per Tenet 2)
- Implement measures to protect and enhance species and system adaptive capacity (with respect to climate, other stressors, and their synergisms) and species potential for microevolutionary change.

Corresponding strategies could include the following:

- Supplementing the list of species and systems of conservation concern with those elements not currently considered at risk but which may become so due to their climate vulnerability (e.g., Horn 2011).
- Preferentially increasing conservation goals (quantity and quality of sites) for species and systems identified as most vulnerable to climate change (e.g., Horn 2011; Howard and Carver 2011).
- Selecting landscape units that increase landscape and regional connectivity and increase buffering from other threats to reduce species and system vulnerability (e.g., Kittel et al. 2011c).

These goals and strategies are consistent with conservation practice employed for other threats (Groves 2003), and so do not rely on any innovation other than to treat climate as an additional threat with its own attributes (Kittel et al. 2011c). Ideally, this is a 'no regrets' strategy as it encompasses conservation actions that would have been called for without explicit consideration of climate issues and, by supporting adaptive capacity, has benefits in regard to other threats regardless of whether climate substantially changes or not (Howard et al. 2010; Wilby and Vaughan 2011). These actions are more likely 'least regrets,' as opposed to 'no regrets,' because of implementation or opportunity costs associated with increases in or some shifting of conservation priorities (Wilby and Vaughan 2011).

Severe-Disruption Strategy

In the longer term, such as over the next 70–100 years, we can consider the possibility that climatic conditions could change so much that there is little expectation that ecosystems would be the same or that any species of concern would be locally retained (Araújo et al. 2004; Bachelet et al. 2001). Such a severe disruption requires that we consider substantially different adaptation strategies and conservation goals (Seastedt et al. 2008).

Given the uncertain status of local and regional biodiversity under this scenario, an approach is to look beyond biological attributes of a landscape and consider how the physical landscape supports biodiversity (without any expectation of what ecosystems may arise there with time) (Kittel et al. 2011a). A strategy is to select landscapes (1) for current physical integrity (with little disruption of, for example, hydrologic network function and soil and geomorphologic processes) and (2) to capture a region's physiographic diversity (e.g., based on elevation, slope, aspect, stream order, lake basin attributes, and bedrock geology). Such landscapes may offer the best prospect for retention of intact ecological and evolutionary processes and for future development of new functioning ecosystems (Anderson and Ferree 2010; Beier and Brost 2010; Cowling et al. 1999; Kittel et al. 2011a). As 'enduring landscapes,' these physical landscapes are largely defined by their topographic and geologic character and so are generally not sensitive to climate changes at ecological timescales (unless significant changes in geomorphology result from climate shifts, for example).

4.15.4.3.4 Tenet 4: Expect Surprises—Scenario Planning

As noted earlier, species or system vulnerability is relative to the magnitude and nature of a threat. While moderate- and severe-disruption contexts (Tenet 3) give us the opportunity to develop generalized magnitude-linked strategies, we can also employ 'scenario planning' to consider vulnerability under a suite of more specific, qualitatively distinct alternative future states. Derived from military and business applications for dealing with high uncertainty, conservation scenario planning generates a limited set of 'what if' scenarios selected to reflect the breadth of probable – as well as less probable but still plausible – futures (Peterson et al. 2003). These form alternative reference frames for assessing species and system vulnerabilities on which to base a suite of conservation strategies. This approach can be implemented by a team of experts offering diverse perspectives, drawn from multiple disciplines and professional backgrounds (e.g., from nongovernmental organizations, agencies, and research institutions) (Kittel et al. 2011c; MacMillan and Marshall 2006; Peterson et al. 2003; Runge et al. 2011).

In contrast to projections that (1) suggest a probabilistic relationship between altered drivers and outcomes (with the probability usually implied but not known or quantifiable) (MacCracken 2001) and (2) commonly are used in climate impact assessments (e.g., Fischlin et al. 2007), scenarios reflect the possible rather than just the probable and can be the foundation of vulnerability assessments (Kittel et al. 2011c; Peterson et al. 2003). Scenarios can be general or specific statements of contrasting future states and can be developed from observed system behavior, system sensitivity from model projections, and 'imaginative speculation' – the last is to challenge our thinking about future dynamics beyond those experienced or expected (Peterson et al. 2003; Turner et al. 2003; an example application in conservation planning is given in Horn 2011, Howard and Carver 2011, and Kittel et al. 2011c).

4.15.4.3.5 Tenet 5: Save Aggressively and Early

If uncertainty is so large that site diversity, multiple time horizon, and scenario planning strategies (Tenets 2–4) seem insufficient, the fallback hedge against uncertainty is to implement conservation action more extensively across the landscape ("Save aggressively to counter downside risk"). An example would be to have greater redundancy in the number of sites fulfilling any one goal. This would likely expand conservation site selection into lower priority, low quality areas (e.g., Kittel et al. 2011c) and might call for restoration to realize the potential adaptive capacity of these landscapes. As with any conservation plan, a complementary strategy is to implement its components as soon as feasible given that opportunity costs (lost opportunities) for protecting habitats and landscapes increase with time, as key environments are degraded by other stressors ("Start investing early"); this need is only intensified with climatic uncertainty (Hannah et al. 2007).

In conservation planning, the question of "How much is enough?" is one difficult to address (1) because of uncertainty in future levels of risk from both known and unanticipated threats and (2) because, for more pragmatic considerations, conservation plans often call for a level of action greater than feasible given limited opportunity and financial resources. That said, high uncertainty in climate risk ups the level of critical conservation action needed to reduce the vulnerability of species and ecosystems and should provide additional incentive for action by agencies, conservation organizations, and other public and private stakeholders.

4.15.4.3.6 Tenet 6: Revisit Goals and Strategies—Adaptive Management

A conservation plan for reducing climate vulnerability needs to include a review process for keeping the plan on goal by incorporating monitoring feedback and new information ("Periodically reevaluate financial goals, adjust investment strategies accordingly"). This is to help cope with uncertainties in how conservation strategies will play out due to unexpected species and system dynamics and unanticipated changes in external forcings (including from new threats).

One approach for on going reassessment in conservation planning is 'adaptive management' (Keith et al. 2011). Adaptive management is an iterative process of (1) reassessing species and system status through monitoring, (2) evaluating current and alternative innovative strategies through research and expert elicitation, and (3) adapting conservation plans in light of these new insights (Conroy et al. 2011; Runge et al. 2011; Williams et al. 2007). The adaptive process could include periodic reappraisal of goals, vulnerability assessments, and strategies to take into consideration:

- Observed changes to populations, communities, and ecosystems – including those tied to conservation plan achievements and failures to date.
- Increased understanding of external forcing and internal dynamics.
- New opportunities – such as from new ideas, tools, stakeholders, and government policies.

4.15.4.4 A Vulnerability Approach for Conservation Planning

Consideration of climate in conservation planning often takes the form of impact assessments, where the goal reflects a perceived need to determine specifics of how, where, and which elements of biodiversity might be strongly altered under rapid climate change. Explicitly driven by climate projections, this approach is referred to as 'top down' as it follows the progression of cause and effect. However, this requires skillful prediction and a certainty in future forcings – which, in all practicality, are not achievable (see Section 2.01.2 and Section 4.15.4.2). Consequently, high uncertainty and low predictability limit the value of model projections for conservation planning. Such limitations include that (1) spatial and temporal details in projections are not definitive enough to be relied on for planning, even when downscaled, (2) the use of ensembles of projections to capture a range of outcomes still constrains our outlook, as they (most likely) underrepresent a larger domain of possible futures that may arise from unforeseen or poorly modeled forcings and dynamics, and (3) projections do not necessarily capture critical attributes of climate relevant to understanding ecological, hydrological, and other terrestrial and aquatic processes (such as key variables at appropriate timescales) (Kittel et al. 2011c).

Alternatively, if we acknowledge that high uncertainty in future outlooks cannot be sufficiently reduced, it may be more productive to rephrase our goal to one of decreasing the vulnerability of species and systems (Dawson et al. 2011; Kittel et al. 2011c). This 'vulnerability approach' focuses on enhancing adaptive capacity as a means to lower or cope with risks from uncertainties (Pielke et al. 2012; Turner et al. 2003). In contrast to projection-driven assessments, this is a 'bottom-up' approach as it looks to understand species and ecosystem dynamics that determine their vulnerability (Pielke et al. 2012). This approach focuses on producing planning outcomes that better recognize and handle uncertainties, employing strategies that do not rely on the temporal and geographic details of model projections (Kittel et al. 2011c).

In the vulnerability approach, the investment-analog tenets (see Section 4.15.4.3) give us a framework for handling uncertainty in a 'smart' (appropriate) manner while devising strategies to support the adaptive capacity of species and systems. Stemming from these tenets, planning decisions are facilitated by the integration of expert knowledge, scenario planning, a no-regrets goal, and adaptive management as follows:

- Expert synthesis of established knowledge provides an opportunity to gain insights into the resistance and resilience of species and systems to a changing climate and, based on this, to devise strategies to reduce or cope with this risk (Dawson et al. 2011) (see also Comer et al. 2012; Game et al. 2011; Hannah et al. 2002b; Hansen et al. 2010; Mawdsley et al. 2009).
- Scenario planning gives us the means to not rely on climate and ecological model projections for systems whose complexities are, as previously described, inherently difficult to simulate; rather, scenario planning gives us a framework with which to envision consequences to biodiversity across a broad spectrum of plausible futures (including conceivable 'surprises').
- A no-regrets goal guides us to implement climate-adaptive strategies that benefit current conservation needs by also decreasing species and system vulnerabilities to the suite of other threats.
- Adaptive management protocols give conservation programs the flexibility to adjust strategies to changing conditions and advances in our understanding.

The broader the perspective and more integrative the expert synthesis is in its consideration of fundamental determinants of biodiversity's vulnerability to climate the better. This calls for a suite of short- and long-term (multiple planning horizon) climate-adaptive measures to sustain or restore (1) population viability, dispersal, and microevolutionary processes, (2) trophic, competitive, and mutualistic community networks, (3) landscape disturbance regimes, and (4) ecosystem energy and material flows. The resulting design is to support, at least for the near-term, existing patterns of compositional, structural, and functional biodiversity and, in the longer term, to allow for their potential reconfiguration on the landscape as climatic conditions shift.

Such strategies can be devised and deployed using current best conservation practices, including those for maintenance and reestablishment of the physical and biological integrity of the environment, along with reduction of direct and synergistic effects of other threats. Also derived from the tenets for coping with climatic uncertainty, strategic options include diversification, restoration, enhancement of buffering and connectivity, 'enduring landscape' conservation, and 'save more/save early' actions.

This process is clearly inexact, limited by our understanding of species and system adaptive capacity (see Section 4.15.3) and inherent constraints on environmental predictability. Given the essential yet difficult task of conservation planning in light of biodiversity's vulnerability to climate change, the vulnerability approach, integrated with strategies to handle uncertainty, offers a path for us to prepare, even if reluctantly, for an uncertain ecological future.

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See also: Vulnerability of Pollination Ecosystem Services; Sea-Level Rise and Coastal Ecosystems; Biodiversity – Marine Food-Web Structure, Stability, and Regime Shifts; Terrestrial Food Webs and Vulnerability of the Structure and Functioning of Ecosystems to Climate; Desertification of Rangelands; Vulnerability of Coral Reefs; Assessing Cumulative Risks to Ecosystem Function: Expectations and Realities of Environmental Change Interaction Effects; Vulnerability of Estuaries to Climate Change; Vulnerability and Adaptation to Climate Change in the Canadian Arctic.

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4.16 Biodiversity – Marine Food-Web Structure, Stability, and Regime Shifts

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4.16.1 Introduction

Globally, biodiversity is being gradually threatened by increased human impact on ecosystems that cause widespread change in the global distribution of organisms by species extinctions and homogenization through species invasion (Vitousek et al. 1997; McCann 2000; Sala et al. 2000; MEA 2005). These impacts on ecosystems and biodiversity alter ecosystem processes, function, and structure and by that change their stability in face of environmental factors. At the moment, we are in the middle of one of the largest experiments in the history of the earth, as the human effects on climate, biogeochemical cycles, atmospheric nitrogen deposition, and the transportation of organisms have altered the local and global diversity with major consequences for ecosystems and society (Chapin et al. 2000). This has profound implications for the provision of services that humans derive from ecosystems.

Directional changes in climate are among the major factors affecting organisms and biodiversity (Hughes 2000; Root et al. 2005; Walther et al. 2005; Parmesan 2006). Therefore, assessing the biodiversity consequences of changes in weather conditions that organisms experience is a multifaceted problem, requiring consideration of all aspects of vulnerability: exposure, sensitivity, and adaptive capacity (Williams et al. 2008), where (1) exposure is the extent of environmental change likely to be experienced by a species; (2) sensitivity is the degree to which the survival, persistence, fitness, performance, or regeneration of a species or population is dependent on the prevailing climate; and (3) adaptive capacity refers to the capacity of a species to cope with change by persisting in situ, by shifting to more suitable local microhabitats, or by migrating to more suitable regions. All in all, vulnerability has been defined as "the extent to which a species or population is threatened with decline, reduced fitness, genetic loss, or extinction owing to climate change" (Dawson et al. 2011). Vulnerability is also due to other environmental change factors and the interaction effects generated by these factors as well as to climate even if it does not change.

In the following chapter, we will discuss and present state-of-the-art knowledge on the climate effects on biodiversity, and biodiversity effects on marine food-web structure. Then more specifically, we will apply the concept of regime shifts to illustrate how vulnerable marine ecosystems are due to alterations in diversity and stability leading to increased risk of regime shifts in changing environments.

4.16.2 Biodiversity and Temperature

Temperature directly affects the physiology of species (Hughes 2000) and species have been shown to shift their ranges in latitude or altitude (Parmesan 2006; Beaugrand et al. 2009) to adapt to changes in temperature. Further, many species alter their phenology to an earlier timing of spring events or a later timing of autumn events (Blenckner and Hillebrand 2002; Walther et al. 2002; Parmesan 2006). Such changes in phenology may affect species interactions and can cause temporal mismatches of predator–prey interactions, resulting partly in ecosystem-wide effects (Stenseth and Mysterud 2002; Beaugrand et al. 2003; Edwards and Richardson 2004).

In addition to physiological and phenological changes, how temperature could affect biodiversity is very difficult to predict, because often it involves a stochastic interplay of multiple drivers (not only climate) acting on diverse spatial and temporal scales. The Intergovernmental Panel on Climate Change predicted that 20–30% of all organisms have a high risk of extinction if the global mean air temperature exceeds 2 °C (IPCC 2007). The cause for such relative high extinction likelihood is related to ecological and/or geographical boundaries wherein species are assumed not able to disperse or to adapt to the new climate conditions. However, changing climate conditions can also open a window of opportunity for new species invasions; if invasion or colonization processes are faster than extinction, biodiversity could increase in given locales. For example, in the North Sea, an increase in the water temperature during the last decades caused an increase in species richness owing to an increase in warm-water species (Beaugrand 2002; Hiddink and ter Hofstede 2008). This illustrates the difficulty to predict a general biodiversity response to changes in water temperature.

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It is important to note that for most temperature change scenarios, species will not be pushed outside their physiological limits because of changes in temperature. We would expect that more often temperature changes would affect the nature of species interactions. In particular, temperature can affect competitive dominance (Tilman et al. 1986) and further accelerate competitive exclusion (Vijverberg and Vos 2006). Even before species are lost from a system due to such competitive exclusion, changes in the dominance of certain species may have important implications for ecosystem function (Hillebrand et al. 2008). The changes in competition also affect consumption, which alone is strongly temperature dependent. For example, the selectivity and grazing pressure of zooplankton can affect the diversity, evenness, and productivity of phytoplankton (Hillebrand et al. 2007). However, we know little about how diversity is affected by interactions between competitive exclusion, consumption, and temperature, particularly in real life food-webs.

Most of the studies testing climate effects on diversity in marine systems focus on changes in average sea temperature. However, past observational evidences and climate projections argue for a possible increase of variability in these factors. Other human-induced environmental changes increase the risk of extreme values in environmental characteristics which will influence species richness and stability (Carpenter and Brock 2006; Ives and Carpenter 2007). For example, increased variability in salinity (Flöder and Burns 2004), temperature (Descamps-Julien and Gonzalez 2005), and nutrients (Sommer 1985) increase species richness by preventing competitive exclusions. However, the combined effects of the change in the mean and in the variation are very poorly understood and most probably highly ecosystem specific. For example, zooplankton diversity has been found to increase with changes in temperature but to decrease with variations in chemical variables (Shurin et al. 2010).

4.16.3 Diversity versus Stability – a Long Debate

The relationship between diversity and ecosystem stability has fascinated ecologists over decades. In the 1950s, ecologists suggested that a more diverse community enhances ecosystem stability (Odum 1953; MacArthur 1955; Elton 1958). This ecological theory was for a long time mainly based on equilibrium population dynamics. However, populations often show large temporal and spatial variation. Because such variations can significantly influence ecological dynamics, ecologists moved away from an equilibrium-based concept of stability to one generated by temporal variability in environmental factors (McCann 2000). This is of special importance because fluctuations of populations are driven by biotic or abiotic processes, which provide the possibility that a large number of organisms, for example phytoplankton species, can coexist in the water column on a minimal number of resources (see, e.g., the paradox of phytoplankton; Huisman and Weissing 1999 and literature therein).

In general, stability can be measured in several ways (see for different definitions Ives and Carpenter 2007). For example, for a rare perturbation, stability can be measured as the rate as the system returns back to the equilibrium state (May 1973), also defined as engineering resilience (Holling 1996). In cases in which perturbations are stochastic and of higher frequency, stability depends on community resistance (Pimm 1984), which can be measured by the variability in the change of combined species densities over time with repeated perturbations (Ives and Carpenter 2007). These two measures of stability combine to give a third measure: overall system variability. Further, Ives and Carpenter (2007) point to cases wherein stability could be measured as the number of species within an area that are extirpated, or by the compensatory change in combined densities of all species. Another possibility is that perturbations might even cause the invasion of new species and here stability could be measured as the chance that an invader is successful, or the number of secondary extinctions the invasion causes (Ives and Carpenter 2007 and lit therein). These different ways to measure stability illustrates how differently external perturbations can shape the food-web dynamics and thereby the stability.

A majority of diversity-stability studies focus on single trophic level response in the context of relationships. For example, long-term grassland experiments suggested that diversity within an ecosystem tends to be correlated positively with plant community stability measured as the coefficient of variation of plant biomass (Tilman et al. 1996). Functional diversity, rather than species diversity, tends to most strongly relate to stability (Huston 1997; Tilman et al. 1997; Hooper et al. 2005). This is important because the diversity of responses to environmental change among species contributing to the same ecosystem function, which is called response diversity, is critical to stability, that is, ecosystem resilience (Elmqvist et al. 2003). Thus diversity is not the direct driver of the stability of ecosystems (McCann 2000). Instead, it seems that species diversity provides a pool of important ecological mechanisms and response patterns that are essential for the stability in ecosystems. The greater the variances in species responses, the lower the species richness required to insure the ecosystem, also known as an insurance hypothesis (Yachi and Loreau 1999). By further applying the food-web approach instead of the often-used linear food-chain approach, models and experiments showed that natural food-web structures can increase the ecosystem stability (McCann 2000 and lit therein). This valuable insight has led to a discovery of an important mechanism where weakly interacting species stabilize community dynamics by dampening strong, potentially destabilizing consumer–resource interactions. Here the number, distribution, and variability of weak interactions in a food-web can be of high importance (McCann 2000) and any addition or removal of key species can have profound effects on the ecosystem stability (McCann 2000). Thus, decreasing biodiversity may often be accompanied by increases in average interaction strengths among species and a concomitant decrease in ecosystem stability.

4.16.4 The Vulnerability of Ecosystem Stability and Regime Shifts

As described above, in natural systems populations tend to fluctuate around some trend or average. However, populations occasionally experience a regime shift that is characterized by an abrupt change in the structure and function of a system.

Recently, it has been shown in experiments and field data that a gradual change in external drivers (e.g., temperature) can cause an abrupt, nonlinear change in an ecosystem (May 1973; Scheffer et al. 2001; Scheffer and Carpenter 2003; Folke et al. 2004). Even a small change in environmental conditions can trigger a large shift in ecosystems. The reason for such an abrupt shift is the decrease in the ecosystem stability, wherein several factors have eroded the stability (resilience) so that sometimes only a tiny change can act as the straw that broke the camel's back, causing an entire regime shift.

After a system has crossed a threshold, the ecosystem dynamics and functions are different from prior observations (Scheffer et al. 2001). For example, if a lake ecosystem has experienced eutrophication due to the addition of a nutrient load, the ecosystem becomes more dominated by phytoplankton instead of aquatic macrophytes and benthic organisms that are found in less-eutrophied systems. Even if the external input of nutrients is reduced due to improved management options, the turbid, phytoplankton-dominated state is maintained through constant recycling of nutrients from the lake sediment. In order to return to the previous state, nutrient inputs usually have to be reduced significantly below the threshold level that caused the system to transform to the eutrophic phytoplankton dominant state. This phenomenon is known as hysteresis and characterizes many regime shifts.

Hysteresis is a stabilizing mechanism generated by internal feedbacks associated with the existence of different ecosystem stable states or regimes. In general, both negative (i.e., 'damping' or 'stabilizing') and positive (i.e., 'amplifying' or 'reinforcing') feedbacks are an integral part of all natural systems. Negative feedbacks tend to reduce fluctuations in process rates, keeping the system within a particular state. In contrast, positive feedbacks increase changes in processes that destabilize the system. The strength of species interactions determines the strength of the feedbacks and thus the strength of the hysteresis effects.

External drivers, for instance, changes in climate patterns, can overwhelm negative feedbacks and increase the importance of positive feedbacks. If these positive feedbacks are strong enough in relation to other ecosystem processes, they can drive the system across a threshold. Duarte et al. (2009) discussed that in some cases it might not be possible to return the ecosystem to its previous state even if the pressures are reduced far beyond the preshift levels. How much the external forcing needs to be reduced in order to change the system between different alternative states is determined by the internal feedback mechanisms that make these states persistent (e.g., hypoxia in the Black Sea (Oguz and Gilbert 2007)). According to Scheffer et al. (2001), biological feedbacks, especially predation and competition, are important factors in determining the system states and change between them. Nevertheless, to really pinpoint these mechanisms has proved difficult because they vary in space, time, are system specific (Scheffer et al. 2001), and may first be detectable only after a threshold is exceeded. Furthermore, model studies have suggested that changes in internal ecosystem dynamics (e.g., behavioral change such as schooling (Bakun and Cury 1999; Cury and Shannon 2004) can also result in changes in state and not only stabilize a new state (Scheffer et al. 2001; Scheffer and Carpenter 2003).

One should not expect all ecosystems to respond to climate in an abrupt continuous manner. Scheffer et al. (2001) and Collie et al. (2004) describe different response types in ecosystem change based on the relationship between the response (ecosystem) and control (external) variables. This relationship can be linear/smooth, nonlinear/abrupt, or discontinuous, leading to alternate regimes and hysteresis. When studying such responses, it is worth keeping in mind that the ecosystem response reflects the lifecycle length of response 'groups' and hence, for example, plankton organisms are likely to respond faster than those at higher trophic levels (Overton 1972; Wagner and Adrian 2009).

The regime shift concept has increasingly been employed in various ways in describing an array of changes in environments during the past decade. Nevertheless, the problem of defining a change as a regime shift was brought into discussion rather recently. Lees et al. (2006) are one of the first to attempt to set up common criteria for defining a marine ecosystem regime shift. They based their study on previously published descriptions and concluded that the criteria used to define both climatic and ecosystem regime shifts have been very system specific.

According to qualitative criteria, an ecosystem regime shift is a sudden, high-amplitude and infrequent event that has large spatial scale and is detectable in atmospheric and oceanic components as well as affects several trophic levels (Lees et al. 2006). Lees et al. (2006) also demonstrate that many previous studies attempted to quantify regime shifts; meanwhile changes in food-web structure, interaction strength, and dynamics have seldom been recorded. Collie et al. (2004) have also stated that statistical time series analysis is not sufficient on its own to describe regime shifts, but more qualitative mechanistic understanding is needed. In practice, changes in ecosystem indicators, such as species richness and mean trophic level, have been measured, for example, by Tian et al. (2008) in their study of the Japan/East Sea.

4.16.5 Regime Shifts and the Vulnerability of Marine Ecosystems to Climate

Large-scale changes in marine ecosystems with significant environmental as well as economical consequences are observed in increasing numbers worldwide (Cury and Shannon 2004; Folke et al. 2004; Tian et al. 2006; Möllmann et al. 2009). In open sea ecosystems, changes are often associated with overfishing or changes in weather and ocean patterns (Lees et al. 2006). In the case of overfishing, many examples of collapsing, or at least drastically decreasing, fish stocks exist in both coastal and offshore ecosystems (Jackson et al. 2001; Hutchings and Reynolds 2004). Recent declines of cod stocks (*Gadus morhua*) in the Atlantic (Frank et al. 2005), North Sea (Beaugrand 2004), Newfoundland (Hutchings 1996), and Baltic Sea (Casini et al. 2009b) as well as collapses of pelagic fish stocks in the Northern Benguela (Cury and Shannon 2004) and Black Sea (Oguz and Gilbert 2007) are a few well-recognized examples. The best-known stock recovery failure was observed in Newfoundland where cod did not return even after a fishing ban was put into place. Some of the above-mentioned fish stock collapses have also been associated with changes in weather and ocean patterns. The collapse in the Peruvian sardine stock at the beginning of the 1970s was related to El Niño phenomena (Barber and Chavez 1983), and is a prime example of a climate-induced ecological change (Alheit and Bakun 2010). In addition, eutrophication-related ecosystem changes such as the appearance of persistent hypoxia are commonly observed in today's shelf and enclosed seas.

In the following section, we present several cases of marine regime shifts (see **Table 1**) in relation to their timing, the drivers causing the regime shift, the internal food-web dynamics, and characteristics that make the system more vulnerable to change. We limit our scope to published open sea ecosystem changes that are determined as regime shifts by the corresponding authors.

4.16.5.1 Timing of Regime Shifts

The marine ecosystems that are suggested to have undergone a regime shift represent different types of marine environments. The geographical distribution of these ecosystems is wide, but rather Northern Hemisphere centric (**Figure 1**). This is partially explained by the exclusion of coral reef studies from the scope of this study (e.g., Hughes et al. 2007; Norström et al. 2009). Most of the published studies start their time-series from the mid-1960s and continue into the beginning of the present century (**Figure 2**). Two main regime shift periods can be identified, the first at the end of the 1970s and a second, larger one in the late 1980s. The first cluster of studies is mainly composed of regime shifts detected in oceanic Northern latitude ecosystems (Link et al. 2009). During the latter period (1988–90), several independent studies observed regime shifts in ten marine ecosystems with varying characteristics and wide geographical distributions. The timing of the regime shift cluster in the latter half of the 1980s (**Figure 1**) coincides with large-scale changes in the atmosphere, indicated by atmospheric-ocean climate indices such as the Pacific Decadal Oscillation (PDO; Hare and Mantua 2000) and Northern Atlantic Oscillation (NAO, Hurrell 1996). Both indices are calculated by differences in sea-level pressure and consequently sudden changes in seawater temperatures and advection patterns (Hurrell and Deser 2010), often with a connection over large distances (Alheit and Bakun 2010). At present, it is commonly suggested that these changes in the physical environment are closely linked with the marine ecosystem regime shifts observed during that period.

4.16.5.2 External Drivers Causing Regime Shifts

The drivers causing regime shifts can either be single or, most probably, multiple. In many of the marine regime shifts, multiple drivers are found to have initiated the change (see **Figure 3**). Often, the main drivers are atmospheric-ocean patterns, high fishing pressure, and eutrophication initiated by excess anthropogenic nutrient input. However, large oceanic offshore ecosystems form an exception and have been suggested to have undergone regime shifts initiated solely by abrupt changes in atmospheric-ocean patterns (**Figure 3**).

It is worth noting that many studies, especially atmospheric-ocean oriented regime shift studies, wrongly do not consider other drivers in their analysis. Regime shifts suggested to be caused by multiple drivers occurred mostly in coastal areas or semi-enclosed systems. Here the main drivers are climate, fishing, and nutrient loading from land (**Figure 3**). In the Mediterranean Sea, the increase in zooplankton biomass was correlated to changes in climatic conditions, but also an inverse relationship to anchovy biomass was found (Conversi et al. 2010). Hence, it may be misleading to neglect this change in predation pressure when studying the change in zooplankton abundance. Also, in Chesapeake Bay intensive fishing was found to be behind a decline in the total fish stock accompanied by an increase in the pelagic/benthic fish ratio observed after the beginning of the 1990s (Kemp et al. 2005). Hence, even if the

Table 1 Properties and source of marine ecosystem regime shifts

System	*System type*	*Shifts*	*Reference*
Baltic Sea	Brackish, enclosed	1988–1993	Möllmann et al. (2008); Casini et al. (2009a); Möllmann et al. (2009)
Benguela (North)	Upwelling, offshore	Late 1980s	Cury and Shannon (2004)
Bering Sea	Offshore	1976–1978	Benson and Trites (2002); Link et al. (2009)
Black Sea	Enclosed	1973–1974, late 1980s, late 1990s	Daskalov et al. (2007a); Oguz, (2007) Oguz and Gilbert (2007)
Chesapeake Bay	Brackish, enclosed	1986	Conley et al. (2009)
Georges Bank	Upwelling, coastal	1965, 1976–1978, 1987–1989, 1998–1999	Collie et al. (2004); Link et al. (2009)
Gulf of Alaska	Offshore	1977, 1989	Benson and Trites (2002)
Gulf of Maine	Coastal	1976–1978, 1987–1989, 1998–1999	Link et al. (2009)
Gulf of Mexico	Semi-enclosed	1993	Boesch et al. (2001); Rabalais et al. (2002); Conley et al. (2009); Liu and Scavia (2010)
Gulf of St. Lawrence	Enclosed	Mid-1980s	Savenkoff et al. (2007)
Humboldt Current	Offshore	1968–1970, 1984–1986	Alheit and Niquen (2004)
Japan/East Sea	Semi-enclosed	Mid-1970s, late 1980s	Zhang et al. (2007); Tian et al. (2008)
Mediterranean Sea	Semi-enclosed	Late 1980s	Conversi et al. (2010)
North Pacific	Offshore	1977, 1989	Hare and Mantua (2000)
North Sea	Offshore	1982–1988	Beaugrand (2004); Weijerman et al. (2005)

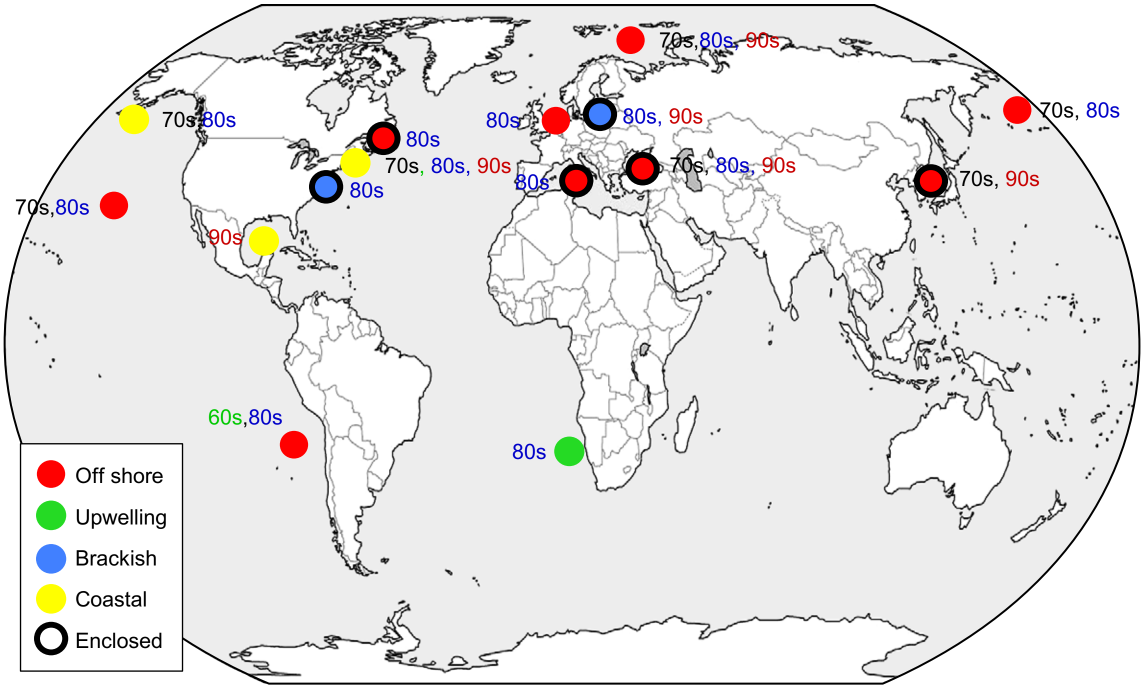
70s, 80s, 90s
70s, 80s
80s
80s, 90s
70s, 80s
80s
70s, 80s, 90s
80s
70s, 80s, 90s
70s, 90s
80s
70s, 80s
90s
60s, 80s
80s
Off shore
Upwelling
Brackish
Coastal
Enclosed

Figure 1 Locations of marine ecosystems that have gone through an ecosystem regime shift and are included in this study. The decade of change is indicated next to location.

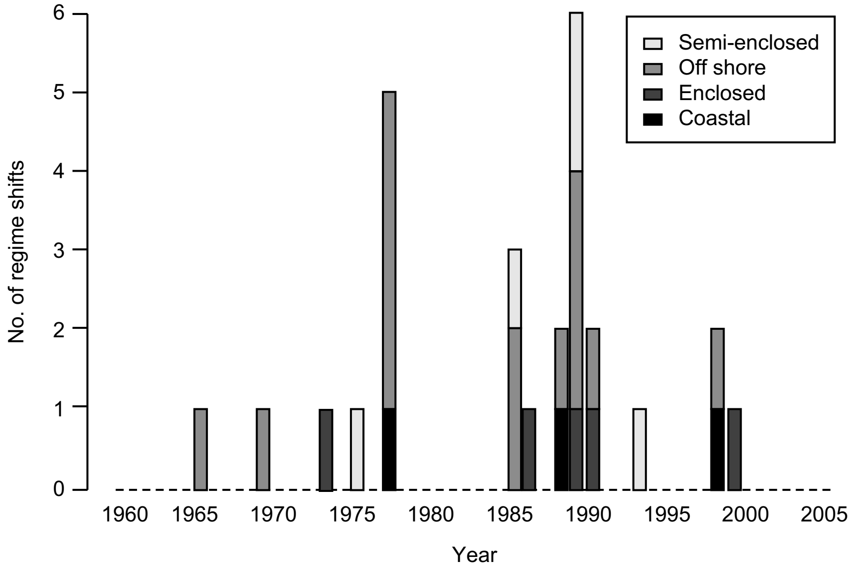

Figure 2 Timing of regime shifts in different types of marine ecosystems.

fishery-related regime shift has not been described in Chesapeake Bay, the fishery may have contributed to the regime shift because overfishing could have caused a lower resilience toward the ecosystem change observed in the early 1990s.

4.16.5.3 Food-Web Structure and System Properties

The ecosystems which have undergone discontinuous ecosystem change have many commonalities in their internal dynamics. For example, the presence of hypoxia and eutrophication is a common feature of the current state of the Black Sea, Baltic Sea, Northern Benguela, Gulf of Mexico, and Chesapeake Bay. In most of the regime shift cases with hypoxia, the vicious cycle of nutrients, eutrophication and hypoxia, is the main focus of regime-shift analysis. In the Baltic Sea, Black Sea, and Northern Benguela ecosystems, however, hypoxia is additionally seen as a mechanism that worsens recruitment conditions of important piscivorous and planktivorous fish,

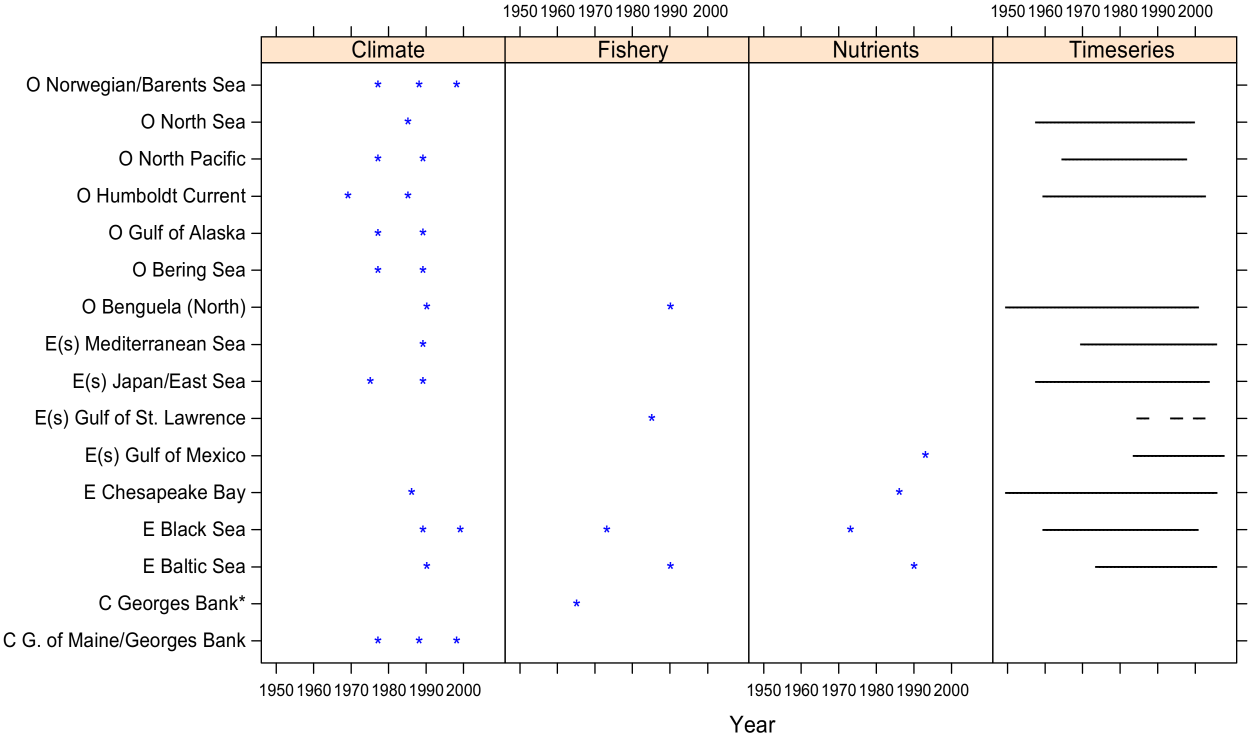

Figure 3 Drivers observed to have caused regime shifts in different types of marine ecosystems (O = oceanic, E(s) = semi-enclosed, E = enclosed, C = coastal) and the length of time-series used in analysis. *Study only on haddock, time-series length 1931–2000 (not included in the graph due to scaling). Information on the length of time-series studied was not available from all studies.

hence altering the top-down control in these systems once present.

Related to eutrophication, invasive zooplanktivore jellyfish have been found to play an important role in stabilizing the new eutrophic ecosystem states in the Black Sea and the Northern Benguela. Jellyfish can efficiently prey on zooplankton and thereby decrease the grazing on phytoplankton in these ecosystems (Cury and Shannon 2004; Oguz 2007; Oguz and Gilbert 2007; Oguz et al. 2008). They also efficiently compete for zooplankton prey with planktivorous fish, but themselves are nutritionally poor, and the energy they contain is not channeled to upper trophic levels. The jellyfish (*Mnemiopsis* sp.) have been suggested to appear in the Southern Baltic Sea during the past years (Lehtiniemi et al. 2007; Gorokhova et al. 2009).

Several feedback mechanisms have been suggested (Fauchald 2010) that can contribute toward hysteresis in relation to ecosystem change. These are predator–prey reversal (Köster and Möllmann 2000; Walters and Kitchell 2001), recruitment competition or piscivore preying on planktivorous species that compete/prey on juvenile piscivores (Walters and Kitchell 2001), size-selective predation, and food-dependent growth (see for a model study De Roos and Persson 2002), as well as change in behavior due to risk effects (Willis 2007). Fauchald (2010) emphasizes that these internal feedback mechanisms involve trophic top-down interactions and have also been described to take place between piscivorous predatory fish and their planktivorous prey. In the Baltic Sea, the delayed recovery of cod after decrease in fishing pressure may have to do with cod egg predation by pelagic planktivore sprat (*Sprattus sprattus*), which has exploded after its release from the predation control of cod (Köster and Möllmann 2000). In the North Sea, increased herring stock (*Clupea harengus*) is thought to predate on cod eggs (Fauchald 2010). In the Baltic Sea also, resource competition between cod larvae and adult cod prey sprat has been documented. Both, cod larvae, and sprat prey on the zooplankton *Pseudocalanus* sp. (Möllmann et al. 2004) and the recent cod abundance is too low to control the sprat population (Casini et al. 2009b). Model studies have also indicated that once cod is abundant in the Baltic Sea, the cod may be capable of shaping the size spectra of its prey population to benefit its growth and vice versa (Van Leeuwen et al. 2008). In general, there seems to be a general shift from pelagic or benthic piscivore-dominated systems into ones dominated by small pelagic forage fish (Frank et al. 2005). Out of the hysteresis-displaying systems, the Black Sea (Daskalov et al. 2007b; Oguz and Gilbert 2007), Baltic Sea (Möllmann et al. 2008; Casini et al. 2009b), Gulf of St. Lawrence (Savenkoff et al. 2007), Chesapeake Bay (Kemp et al. 2005), and Georges Bank (Collie et al. 2004) have undergone such a change.

Despite multiple drivers seeming to be connected with discontinuous regime shifts in marine systems, increased nutrient loads or implementations of fisheries are suggested to be able to initiate such a shift on their own. Out of these, the fishery can act as a top-down or wasp-waist (mid-trophic level) control (Cury et al. 2000) and nutrient loads in addition can exert bottom-up control, or wasp waist control via worsened fish breeding conditions due to eutrophication. On the contrary, none of the regime shifts initiated by climate alone shows indication of being discontinuous. This brings up a question whether the ecosystem or populations vulnerability to climate results in a discontinuous regime shift in marine environment. For example, changes in temperature and salinity have been shown to affect fish recruitment success (Köster et al. 2005). Changes in local and regional climatic conditions could alter food-web structure and interaction strength also via altering the top-down and bottom-up dynamics or via change in the functional group diversity caused by extinction and/or invasions of species. Further, it has been suggested that before species are locally extirpated, change in the dominance of these species must occur much earlier (Hillebrand et al. 2008). Increases in temperature can shorten generation times and change interspecific interaction dynamics, which might lead to an increase in species turnover without any change in species richness. Hillebrand et al. (2010) found that temperature increases species turnover and thereby decreased the compositional stability of communities and the functional stability of ecosystem processes without changes in species richness. This again indicates that species richness alone is not a good indicator for the stability in ecosystems and its vulnerability to climate as well as other drivers. Further, local species turnover shown by Hillebrand et al. (2010) will be mediated by more regional changes in species turnover induced by changes in regional climate (Parmesan et al. 1999).

In general, system properties that have been suggested to contribute to stability and herewith to the potential regime shift occurrence in various ways comprise unoccupied space for sessile organisms (Dunstan and Johnson 2004), functional richness (Hooper et al. 2005; Hughes et al. 2005), and species richness (see, e.g., Hooper et al. 2005; Balvanera et al. 2006; Ives and Carpenter 2007).

Frank et al. (2007) suggested species richness to be related to the type of trophic control within the system at each site. Results from the study by Frank et al. (2007) suggest that the level of species richness can be linked to the type of trophic control the ecosystem exhibits. The internal trophic control is thought to play an important role in stabilizing alternative ecosystem states (Scheffer et al. 2001), and species richness is seen to contribute to system resilience.

The restricted water and species exchange in more enclosed systems may limit the dispersal of species and hence also limit functional response diversity, which could explain the more frequent regime shifts in enclosed systems. Further, different anthropogenic drivers also can exert stronger pressure on enclosed systems especially when the coastline and catchment areas are highly populated, which often coincides with high nutrient loads and associated hypoxic areas such as the Baltic Sea.

4.16.6 Outlook

Knowledge on the effect of biodiversity on the food-web structure and stability is still incomplete, despite the very comprehensive and ongoing focus in science. This short overview has, however, shown that biodiversity plays an important role in shaping ecosystem structure and function. In addition, biodiversity seems to be an important component in determining the vulnerability of ecosystems to climate.

It was shown here that a change in ocean and atmospheric weather patterns has triggered several regime shifts within a wide geographical area, but even so the mechanisms behind such changes are still unknown. The group of marine ecosystems showing signs of hysteresis possess some common characteristics, such as enclosed bathymetry and the exposure to multiple anthropogenic drivers. The combined strength of anthropogenic forcing can be larger in these systems or the system resilience may be lower than in more open and/or diverse marine environments. Previously, Collie et al. (2004) have stated that discontinuous regime shifts might not be observable in oceanic ecosystems because they are not spatially confined, hence supporting the observation that marine ecosystems with enclosed nature might be more vulnerable to discontinuous change than open offshore areas. In addition, hypoxia seems to be present in many of the ecosystems suggested to have undergone a discontinuous regime shift, potentially implying that benthic–pelagic coupling has a role in hysteresis-related positive feedback mechanisms. Because hysteresis is a time-dependent phenomenon, the species lifecycle and their interaction strengths are most probably important factors when determining the potential occurrence of discontinuous dynamics. In case of long-lived species, one has to take into account the potential time lag in response and also be prepared that clear abrupt shifts might not always be observable in the time-series of longer-lived species despite whether a discontinuous change would have taken place (Spencer and Collie 1997).

The Baltic Sea is a well-known example of an ecosystem suggested to have undergone an ecosystem-wide discontinuous regime shift in the end of the 1980s (Casini et al. 2008; Möllmann et al. 2009; Alheit and Bakun 2010). Sudden changes in the winter climate (North Atlantic Oscillation, NAO) together with high fishing pressure and a long stagnation period are thought to be shift-triggering causes. Low levels of Baltic cod biomass, explosion of sprat abundance as well as great changes in the abundance of zooplankton species such as *Pseudocalanus* sp. (decrease) and *Acartia* spp. (increase) are characteristic to the new suggested ecosystem state. The winter climate returned back to its pre-1990s state around the late-1990s (Möllmann et al. 2009). However, cod, sprat, and zooplankton species have not yet shown significant change toward their preshift abundances (note that very recently cod stock has shown some signs of recovery as a response to lowered fishing pressure). In addition to changes in fishing pressure, the current internal control mechanisms in the Baltic are suggested to differ from those before the change (Casini et al. 2009a,b). Hence, one can question if the previous zooplankton abundances will be detected in the future or will the predation control on *Pseudocalanus* accuses continue to be a more important control mechanism than the environmental driver of salinity (Casini et al. 2009a,b). Also, on a more general level, it is difficult to say if any marine ecosystem can return to the pre-change ecosystem state due to continuous changes in species composition and internal ecosystem dynamics (Duarte et al. 2009). In other words, ecosystems are a moving target. Even if some individual ecosystem targets might be met from a management point of view, one must be aware of that the return to the desired state might not be ecosystem wide and the current ecosystem response can differ from the previous (Duarte et al. 2009).

The type of response, potentially including discontinuous dynamics, together with changes in internal ecosystem dynamics are seldom more than discussed in the context of marine ecosystem regime shifts. Here, a strong link to ecological theory on diversity and stability is necessary to better understand the ecosystem processes.

Furthermore, it is still debated whether the feedbacks of the discontinuous dynamics need to break down in order for a new, possibly more desirable regime to take place. Such a case has been indicated by model studies (see, e.g., Alley et al. 2003; Oguz 2007), but has proven to be difficult to show in actual ecosystem observations. Regarding ecosystem management, it is of high importance to identify discontinuous dynamics from more linear and smooth changes in ecosystems (Collie et al. 2004), because such systems would require a different management strategy, that is, the reduction of the pressure variable below the threshold ranges.

In many cases it is also challenging to evaluate whether the described change really is ecosystem wide or if a more 'species-replacement' type phenomenon has taken place (Cury and Shannon 2004). To tackle this uncertainty, for example, Tian et al. (2006) have used Simpson's diversity index, mean trophic level in catch, and piscivore/zooplanktivore ratio as ecosystem change indicators. To determine ecosystem vulnerability to external drivers, for example climate, one may employ a common set of methods and indicators to clearly define stability, regime shifts, and hysteresis in experiments, models, and real ecosystems. The significance of earlier detection of change would be great, because currently, the loss in ecosystem resilience and the threshold is often detected only after the threshold has been passed. Some modeling and time-series studies have already been able to give indications for signs of loss in resilience (Biggs et al. 2009). For example ecosystem components may show an increase in variability and change in frequency (Carpenter and Brock 2006), changes in skewness (Guttal and Jayaprakash 2008), slowed down system response (increased autocorrelation) to small perturbations (Dakos et al. 2008), and/or change in the spectral density ratio (Biggs et al. 2009). Such methods have yet to be proven as widely applicable to observational data series that often display a low signal to noise ratio from various environmental drivers and may not be long enough or have sufficiently fine time-resolution. Also these methods might be difficult to apply on higher trophic level organism responses beyond the modeling approach because they have longer life cycles and hence the time-series are likely to display high autocorrelation by default. In the context of marine ecosystem regime shifts, Beaugrand et al. (2008) have recently described an increased ecosystem variability based on time-series data in the north Atlantic. In addition to quantifying and qualifying regime shifts it would be beneficial to describe ecosystem properties in cases in which external drivers have changed drastically but the ecosystem stability was high and therefore no regime shift occurred. That would give a better understanding of (1) the vulnerability of species, in particular following the concept described in Williams et al. (2008) and Dawson et al. (2011), (2) the response diversity, and (3) the strength in interactions, which all most probably provide system stability.

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4.17 Terrestrial Food Webs and Vulnerability of the Structure and Functioning of Ecosystems to Climate

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Glossary

Bottom-up control When soil water and nutrient supplies and plant productivity control the abundance of consumer species and ecosystem functioning.

Community disassembly A nonrandom process that disrupts species interactions leading to alteration of species co-occurrence patterns and loss of ecological functioning.

Ecosystem services The suite of natural resources and ecological functions that benefit human livelihoods and well-being. Examples include provisioning of clean drinking water and decomposition of organic wastes.

Indirect effect The effect of one species on another that is mediated by a third species. For example, predators may indirectly benefit plants by consuming herbivores that eat plants.

Phenological mismatch A condition in which the timing of life-cycle development of interdependent species becomes asynchronous due to the differential ability of species to adjust to environmental changes. Phenological mismatches mean that species may miss the peak period of their food production when they begin to breed, potentially leading to declines in their populations.

Regime shift A rapid reorganization of ecosystems from one state to another. Regime shifts can lead to changes in co-occurrence patterns of species and alter provisioning rates of ecosystem services.

Top-down control When top predators control the species composition and functioning of an ecosystem.

4.17.1 Introduction

An ecological system – ecosystem – can be envisioned as a conception of nature that considers biotic communities comprised of a diversity of species and the biophysical environment as an integrated whole. Species within ecosystems are functionally linked through an intricate network of feeding interdependencies, called food webs, which convey nutrients and energy throughout the ecosystem. The biophysical conditions (soil properties, geology, climate, etc.), in turn, set the context that determines the nature and strength of species interactions and ensuing ecosystem functioning. This conception essentially describes a natural economy of production and consumption chains within which species assume one of four basic functional roles (Figure 1). Plant species (primary producers) draw up water and nutrients from the soil and carbon dioxide from the air and are stimulated by sunlight to convert those different chemicals into tissue. Herbivore species (primary consumers) in turn eat that plant tissue, manufacture and produce animal tissue, and are themselves eaten by predator species (or secondary consumers) that further produce animal tissue. Individuals of plant, herbivore, and predator species that are not eaten by their respective consumers eventually die from aging and the chemical elements of their body are recycled back into the soil by decomposer species.

4.17.2 Food Webs and Ecosystem Services

Fundamentally, food webs are the building blocks that produce the suite of natural resources (fisheries, timber, wildlife game, grazing lands, and natural foods like berries, grains and mushrooms) on which human livelihoods and economic well-being heavily depend. Humans, as ultimate consumers, rely on an appropriate production from all four functional groups of species within food webs. For example, in fisheries, humans typically select predator species (e.g., tuna, swordfish, salmon, and trout) directly from the top of the food web. Game hunting focuses directly on herbivore species (e.g., moose, deer, elk) in the middle of the food web. Timber harvesting focuses on plant

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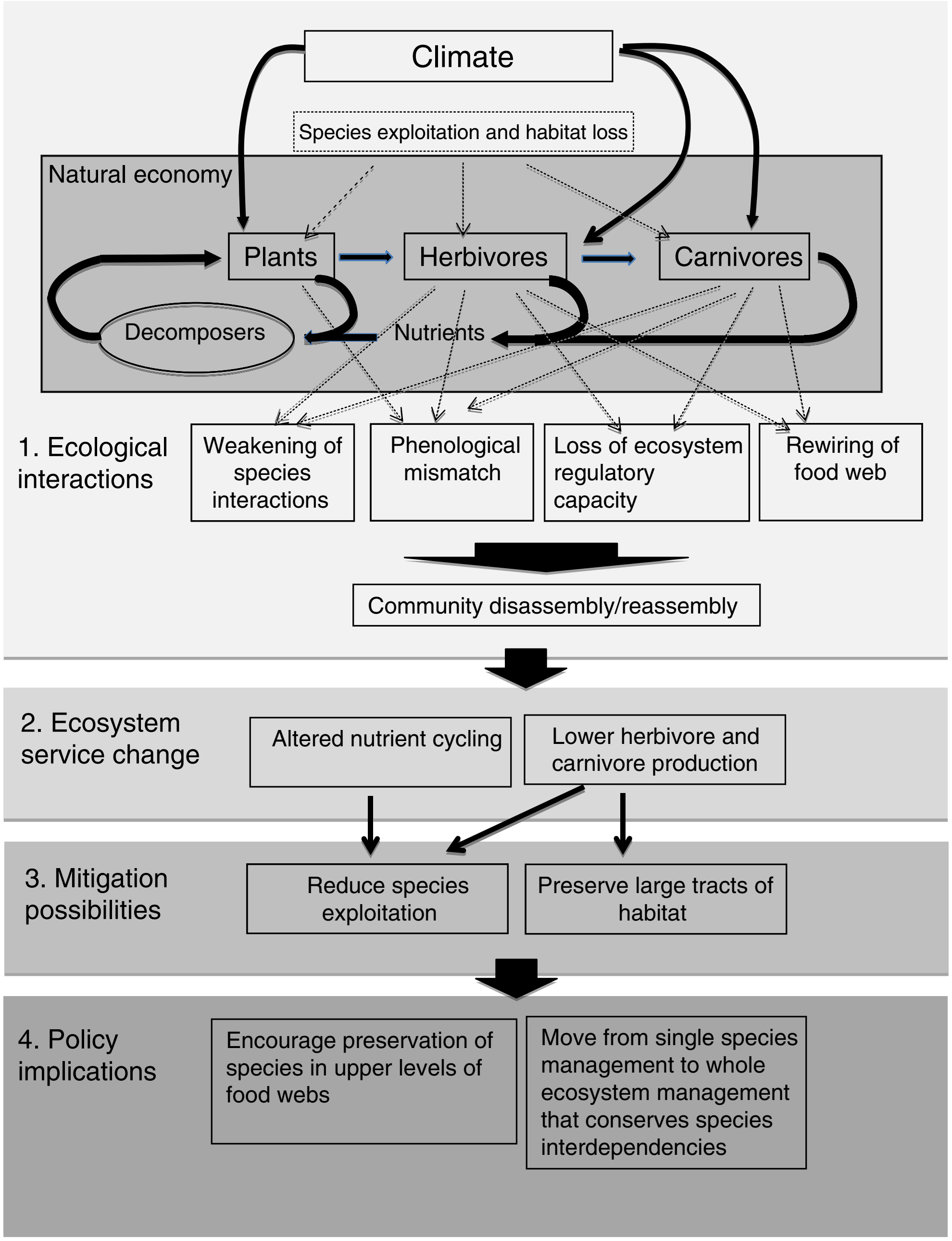
Climate
Species exploitation and habitat loss
Natural economy
Plants
Herbivores
Carnivores
Decomposers
Nutrients
1. Ecological interactions
Weakening of species interactions
Phenological mismatch
Loss of ecosystem regulatory capacity
Rewiring of food web
Community disassembly/reassembly
2. Ecosystem service change
Altered nutrient cycling
Lower herbivore and carnivore production
3. Mitigation possibilities
Reduce species exploitation
Preserve large tracts of habitat
4. Policy implications
Encourage preservation of species in upper levels of food webs
Move from single species management to whole ecosystem management that conserves species interdependencies

Figure 1 Schematic illustrating how climate change may potentially influence terrestrial food webs and associated ecosystem functioning and services. Species of plants, herbivores, carnivores, and decomposers belong to a natural economy. Through their feeding interdependencies, species cycle nutrients and convert nutrients into production. Humans currently exploit plant and animal production for food and for materials. Climate change is expected to influence herbivore and carnivore species, most leading to disruption of nutrient flows and production within the natural economy, and hence, loss of important services to humans. Policies should be developed to protect the natural economy, as a whole, through measures that reduce over-exploitation of herbivores and carnivores and that maintain intact food webs across large tracts of habitats.

species (hardwood and softwood trees) at the bottom of the food web. Humans also appropriate production from food webs by replacing wild grazing herbivore species (e.g., deer, antelope, kangaroos) with domesticated herbivores such as cattle and sheep. Humans can transform and erode food webs through various means such as overexploitation, land conversion from one use to another (e.g., conversion of tropical forests to soybean croplands), through predator control measures that are intended to protect domestic herbivores on grazing lands, and through habitat fragmentation consequent to urbanization. (see Chapter 2.1). Climate change adds a layer of complexity, because species in different parts of the food web will be differentially affected by altered climate statistics (**Figure 1**). In particular, herbivore and carnivore species in upper parts of the food web stand to be affected more than plants. This chapter shows how the nature and level of ecosystem functioning is most sensitive to the loss of these species and why their functional role in ecosystems can be considered more brittle (less resilient) than that of species (e.g., plants) lower down in the food web (Dobson et al. 2009).

4.17.2.1 Food Web Control Over Ecosystem Functioning and Services

Species in food webs contribute to ecosystem functioning and production of services by controlling how nutrients and energy are conveyed and transformed within ecosystems (Vanni 2002; Wardle and Bardgett 2004; Schmitz et al. 2010). Classic thinking in ecology and management holds that nutrient supplies to the bottom of food webs control ecosystem functioning and service provisioning (Schmitz 2008). According to this view, the effects of enhanced nutrient supply should flow up the food web to enhance plant production. Because herbivore and carnivore production is built on plant production, increasing plant primary productivity should enhance the abundance of all species in a food web. It, thus, logically follows that losing or supplanting natural consumer species in upper parts of food webs should have little, if any, bearing on overall ecosystem functioning. However, this view is outmoded (Duffy 2003, Schmitz et al. 2010; Estes et al. 2011). Consumer species exert important negative feedback from the top down to regulate natural resource production through a variety of mechanisms. Thus, adopting a food web perspective to resource management necessarily calls for a bidirectional view of control that includes negative top-down feedback in addition to bottom-up control.

One of the most straightforward examples of negative feedback is the direct effect of predators on prey populations. Empirical syntheses show that vertebrate and invertebrate predators can directly reduce the population sizes of their prey by 25–45% (Salo et al. 2010). Empirical syntheses have further shown that predators can indirectly enhance the abundance of plants by 20–80% through direct interactions with prey (known as a trophic cascade) (Borer et al. 2006). In contrast, empirical syntheses show that enhanced nutrient supplies to plants through fertilization can double plant biomass, but that such enrichment does not carry upward to affect herbivore abundances (Borer et al. 2006). This shows that there is asymmetry in the degree to which bottom-up and top-down effects penetrate food webs to control species abundances.

If negative feedback from consumers can affect plants, then it stands to reason that it should also affect the abundance of different nutrients that determine plant production. Empirical evidence shows that this is indeed the case and arises from a suite of mechanisms that again call into question the primacy of the classic view of control over ecosystem functioning (Schmitz et al. 2010). The classical view holds that microbial species are the most critical driver of ecosystem nutrient dynamics owing to their capacity to convert organic matter into mineral elements for plant uptake and production. Microbial action is thus, believed to be the rate-limiting step in the delivery of inorganic nutrients for primary and secondary production in nutrient limited systems. But animal species can directly and indirectly control the fate of nutrients in ecosystems, and may sometimes circumvent the need for microbial mineralization altogether, depending on how and where nutrients are consumed, translocated, and eliminated. These effects emerge because animals can excrete inorganic nutrients (e.g., urine and guano), they can change the nutrient quality of uneaten organic plant and animal material that eventually enters the soil to be decomposed (and hence indirectly exert control over the rate of decomposition), and they can determine how nutrients are translocated spatially within and across ecosystem boundaries (Vanni 2002; Wardle and Bardgett 2004; Schmitz et al. 2010).

The effects of top-down feedback from animals can be substantial. For example, grizzly bears and river otters consume a variety of fish species from rivers. These consumers carry nutrients from fish up to 1000 m away from streams and redistribute them to localized upland latrine sites into which inorganic nutrients (such as nitrogen and phosphorus) are released (Gende et al. 2002). On a watershed scale, this nutrient input can amount to 15–17% of the total nitrogen content of tree foliage. The nutrient translocation by bears to just the riparian zone (within 500 m of rivers and streams) can amount to 24% of the total riparian zone nitrogen budget. On an area basis, this level of fertilization approaches inputs use by forest managers to sustain timber production in similar kinds of ecosystems.

In some habitats, prey species tend to be disproportionately vulnerable to predation leading to differences in the overall distribution of live prey and locations where they tend to be killed across the landscape. These kill sites, in turn, may become nutrient ‘hotspots.’ For example, on Isle Royale, United States sites containing wolf-killed moose receive a 100–600% higher input of nitrogen, phosphorus, and potassium to the soil relative to nonkill sites (Bump et al. 2009). This input translates into a 25–47% increase in mean foliar nitrogen that lasts for between 14 and 24 months; and a 25% increase in mean foliar quality (measured as the foliar carbon to nitrogen ratio) that lasts even longer (three growing seasons).

Predators carry prey carcasses away from hunting sites to feeding sites (known as central place foraging). This behavior also redistributes nutrients across landscapes. For example, bears can distribute marine-derived nutrients from fish to the surrounding forest by carrying 42.6–68.1% of the salmon they kill away from streams (Schmitz et al. 2010). Such behavior is also evident in a hunting wading bird, the limpkin, which preys on wetland snails that are evenly distributed across open water within the wetland. Up to 80% of captured snails are carried to and consumed within local patches of emergent vegetation (Schmitz et al. 2010). Nutrients derived from empty snail shells and unconsumed snail tissue can enhance levels of total plant biomass and aboveground nitrogen and phosphorus in plants by five fold relative to control plots without limpkins. Input from snail remains is the dominant source of nutrients to these patches, which cover 16% of the area, and create marked heterogeneity in productivity, and patch structure across the wetland landscape (Schmitz et al. 2010).

As mentioned above, predators are most notable for their functional role in controlling prey abundance. Their presence or absence in an ecosystem can have large effects on ecosystem structure. Such strong effects are especially evident on Alaskan islands that have breeding seabird colonies. Sea birds subsidize island nutrient budgets with massive inputs of marine-derived guano. Invading arctic foxes and rats has caused severe reduction in colony sizes that in turn has caused a 98% reduction in guano input (Croll et al. 2005; Estes et al. 2011). The loss of this natural fertilizer has caused dramatic changes to the composition of the plant community that, in some cases, has completely transformed island ecosystems from tundra grassland to tundra shrubland. Finally, a long-term study revealed that levels of plant diversity and plant productivity in a grassland ecosystem comprised of hunting spider predators, grasshopper herbivores and herbaceous grasses, and forbs are governed largely by food web interactions among the top spider predator that causes a generalist grasshopper herbivore to take evasive action by foregoing feeding on preferred grass and hide in and forage on a competitively dominant goldenrod species (Schmitz 2004). Such predator-induced grasshopper suppression of the dominant goldenrod plant alters plant productivity and enhances plant species diversity. A predator removal experiment revealed the release from top-down control enabled the goldenrod to proliferate and overwhelm the plant community within 2 years, because in the absence of predators, grasshoppers significantly reduced feeding on goldenrod and resumed their heavy impact on grasses (Schmitz 2004). Attempts to restore top-down control by reintroducing spider predators failed, because the goldenrod became so abundant that grasshoppers were incapable of suppressing its abundance when they again switched to this resource in the face of predation (Schmitz 2004). In very short order, loss of the top predator caused the ecosystem to undergo a regime shift in which it abruptly tipped from a top-down controlled state to a bottom-up controlled state that was impossible to recover after predators were reintroduced.

The mere threat of predation in prey can also have important implications for ecosystem nutrient cycling. Fear of predation heightens prey stress that in turn changes prey nutrient demands largely from protein nitrogen to support growth and reproduction to soluble carbohydrate carbon to fuel heightened metabolism induced by stress (Hawlena and Schmitz 2010). As described above, grasshopper herbivores select nutrients from a mixture of meadow grasses that offer high levels of protein nitrogen and herb species, specifically the competitively dominant goldenrod plant that provides both a refuge from predation, due to its leafy structure, and an important nutrient source owing to its higher soluble carbohydrate. Chronic physiological stress alters the nutritional quality of organic material input to the soil via three pathways. Chronic predation risk leads to lower nitrogen content in herbivore body tissue, and thus a 6% higher carbon to nitrogen ratio than control conditions, available for decomposition. It also leads to a concomitant 5% higher feces carbon to nitrogen ratio than in control conditions (Hawlena and Schmitz 2010). Finally, chronic predation risk leads to a reduction in the quality (10% higher carbon to nitrogen content than in control conditions) of herb plant tissue that eventually becomes litter (Hawlena and Schmitz 2010). Poorer quality organic matter, as determined by higher carbon to nitrogen ratios, is more recalcitrant to decomposition and can lead to a three fold reduction in carbon mineralization to CO_2 (and hence greater organic carbon retention in soils) relative to predator free conditions (Hawlena et al. 2012). Thus, predators may indirectly control functioning of decomposer species and consequently change decomposition rates.

A dramatic case of ecosystem-wide effects of top-down animal control over ecosystem functioning is revealed in a long-term study of the linkages among herbivore abundance, grazing, wildfires, and the carbon cycle in the 25 000 km^2 Serengeti-Mara ecosystem in East Africa. Prior to the 1960s, Serengeti wildebeest were decimated by disease from introduced domestic cattle and poaching from a once high abundance of about 1.2 million animals down to about 300 000 (Holdo et al. 2009). As a consequence, 80% of the ecosystem was burned annually by wildfire because ungrazed grasslands built up large fuel loads each year. These wildfires also decimated savanna woodlands. Since the 1960s, wildebeest recovery has reversed the trend in spatial extent of the wildfires, and indeed, every increase of 100 000 animals translates into 10% less area burned (Holdo et al. 2009). The wildebeest population seems to have recovered to its historically high level, which in turn has restored the grazing regime and the savanna woodlands. These changes to ecosystem plant structure have also transformed the Serengeti ecosystem from being a net source of carbon to the atmosphere, to a net sink of carbon from the atmosphere. The carbon is stored in tree biomass and in organic matter within soil pools (Holdo et al. 2009). The annual amount of carbon that is now stored in this ecosystem is sufficient to offset annual carbon emissions from air travel to East Africa (Dobson 2009; Holdo et al. 2009). By contrast, three times this amount of carbon was released into the atmosphere when wildebeest were at their lowest abundance (See Chapter 3.1.2).

4.17.2.2 Vulnerability of Food Webs and Ecosystem Services to Human Impacts

Human impacts tend to be unequally distributed throughout food webs. Growing evidence reveals that consumer species in upper parts of the food web, especially predators, tend to be disproportionately vulnerable to human impacts, because they require absolutely more habitat space than other species, they are often either the focus of harvesting or the target of persecution when human–wildlife conflicts arise, and they succumb from unwitting management mistakes that arise from well intentioned efforts to enhance their abundances (Dobson et al. 2009; Strong and Frank 2010). Loss of a few key species can trigger a cascade of further changes to the species composition and the degree of feeding interdependencies among remaining species in food webs, a process known as community disassembly (Zavaleta et al. 2009). Community disassembly can ultimately compromise ecosystem structure and functioning, sometimes with spillover or indirect effects that reach far beyond the focal food web itself.

As one example, a major portion of grassland ecosystems in the western United States has been appropriated for cattle grazing and cereal crop production that latter being heavily reliant on water for irrigation. Historically, grasslands harbored large predators like wolves and grizzly bears. But these predators preyed on cattle and thus, jeopardized the cattle industry. Because of the threat to human livelihoods, these large predators were systematically extirpated from much of their historical range. This has had the linked consequence of loss of water quality and quantity via effects that propagate through the food web (Beschta and Ripple 2006). Over the long term, loss of predators is linked to an increase in the densities of native herbivores such as elk and moose. These species have at times reached such high abundances that they were able to damage riparian habitat through overbrowsing. The loss of species that are reliant on riparian habitat notwithstanding, overbrowsing can destabilize river and stream banks leading to bank erosion, alteration of river and stream channels with attendant effects on the water table, water quality, and intensity and volume of water flow – the very water that is needed to irrigate cereal crops (Beschta and Ripple 2006). Eliminating an important predator species to mitigate threats in one agricultural economy can thus, unintentionally lead to a serious threat to another agricultural economy. Another example concerns management efforts aimed at enhancing the abundance of landlocked Kokanee salmon in several lakes in Montana (Spencer et al. 1991; Ellis et al. 2011). Managers introduced freshwater shrimp to those lakes in order to supplement the Kokanee's diet and enhance the production of this important fishery. But, the salmon did not eat the shrimp. Moreover, the shrimp were voracious predators of an important natural food source for the salmon causing the collapse of the salmon fishery. This loss had ripple effects to the surrounding food webs in terrestrial ecosystem because many species of birds and mammals, including bald eagles and grizzly bears, depend on spawning salmon, as a key food source (Ellis et al. 2011). Here, food web manipulations to enhance an economy unintentionally lead to its collapse with attendant threats to a linked adjacent food web.

These unintended management outcomes stem largely from a classical management worldview that food web structure and ensuing ecosystem functioning is unidirectionally controlled from the bottom-up. The unintended outcomes also arise because of a management focus on single species or resources, with limited if any considerations of how those species and resources are directly and indirectly linked through the lines of dependency in food webs.

The recognition that there is asymmetry in the degree of top-down and bottom-up control of ecosystem functioning due to food web interactions and feedbacks means that ecosystems are differentially vulnerable to human-caused loss of species from different parts of the food web (Duffy 2003; Strong and Frank 2010). Because the loss of species in upper parts of the food webs has far greater ripple effects than do losses of species lower down in the food web, the nature and level of ecosystem functioning is more sensitive to the loss of these species compared to species lower down in the food web. Hence, the functional role of upper level species (especially predators) is classified as being more brittle (less resilient) than that of species (e.g., plants) lower down in the food web (Dobson et al. 2009). This brittleness has important implications for understanding the effects of climate on ecosystem functioning, because climate also has disproportionate effects on species in upper trophic levels of food webs, and thus, stands to conflate the effects of humans on ecosystems (Voight et al. 2003; Zarnetske et al. 2012).

4.17.3 Climate and Ecosystem Structure and Functioning

Climate can alter ecosystem functioning and services by altering the lines of dependency among species in food webs in several ways (Harrington et al. 1999; Schmitz et al. 2003; Tylianakis et al. 2008; Traill et al. 2010; Van der Putten et al. 2010) (Figure 1). Temperature and precipitation changes, for example, can alter the strength and hence, relative importance of top-down and bottom-up control possibly leading to a shift in ecosystem state – called a regime shift – and alteration of ecosystem service provisioning (Schmitz et al. 2003). Climate can have differential effects on species in food webs by altering the level of the factor controlling their populations (Stenseth et al. 2002; Traill et al. 2010). Temperature and precipitation changes can alter the synchrony in timing of life-cycle development of species of prey and predator – called phenological mismatch – that compromises existing feeding dependencies because prey availability becomes less reliable (Post et al. 2008; Both et al. 2009). As a consequence, the feeding dependencies among species go awry leading to loss in levels of ecosystem services like production (Figure 2). Finally, these alterations in typical weather patterns can disassemble existing food webs by changing the way species interact with each other (e.g., cause a switch from being competitors with each other to being predators of each other) or reassemble food webs in new ways depending on how species forge new feeding dependencies (Barton and Schmitz 2009). The following highlights case examples of these different effects.

4.17.3.1 Weakening of Species Interactions due to Differential Vulnerability of Species to Climate

Species within food webs do not respond in identical ways to climate owing to differences in their susceptibility to variations in weather patterns. This variation may affect how and when top-down and bottom-up factors control their abundances.

El Niño Southern Oscillation (ENSO) is a phenomenon that NAO creates periodic changes in weather patterns. ENSO in particular causes large changes in rainfall events that cycle over a 5-year period. A 14-year field study in an arid Chilean ecosystem revealed that influxes of high rainfall during ENSO events became manifest in different ways in the food web (Lima et al. 2002). The food web was comprised of three dominant mouse species, each have differing diets ranging from entirely herbivorous, omnivorous (herbivorous and insectivorous), and entirely insectivorous. Each mouse species' abundance fluctuated with ENSO periodicity because their resources varied strongly with the amount of water input from rainfall (a bottom-up control). However, the strictly herbivorous mouse species was also strongly controlled by two owl species (a top-down control), because it is the owls' preferred food resource. Consequently, the abundance of this mouse species fluctuated much less with ENSO periodicity than did the other two mouse species. This shows again that top-down control by predators may be an important stabilizing factor on species dynamics in food webs with respect to climate.

Another field study spanning 20 years examined how among year differences in the abundances of herbaceous plant species, insect herbivores and arthropod predators could be

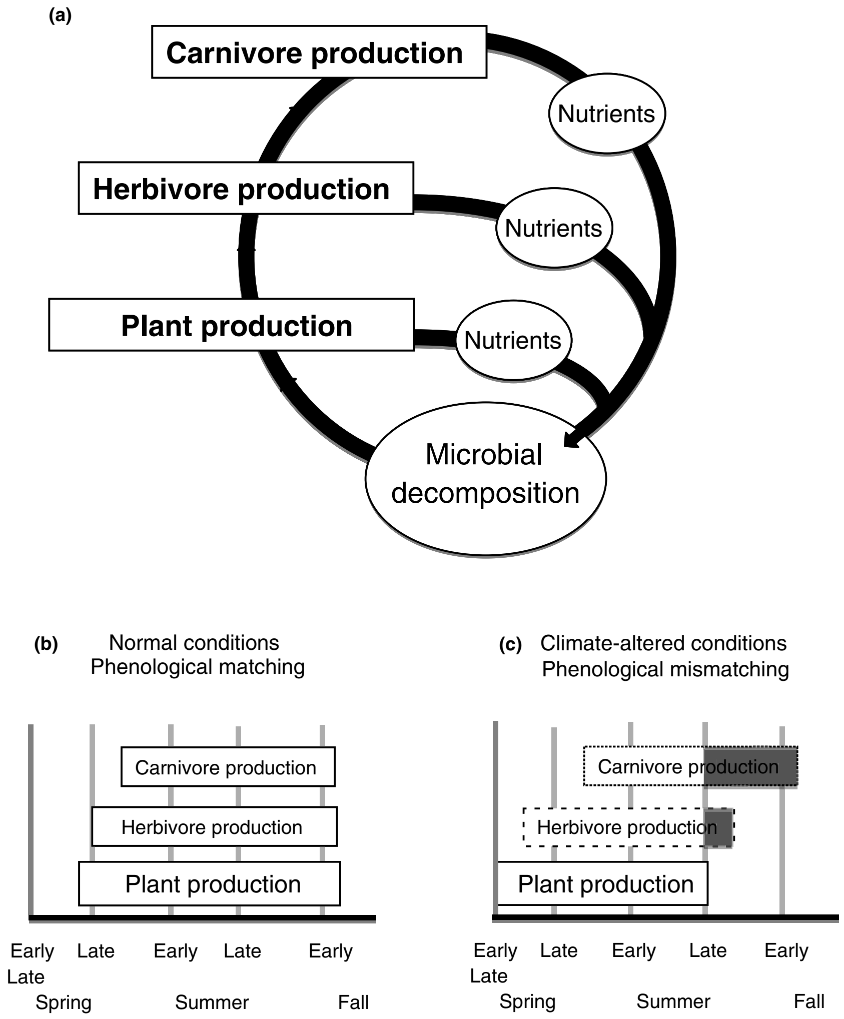
(a)
Carnivore production
Herbivore production
Plant production
Nutrients
Nutrients
Nutrients
Microbial decomposition
(b) Normal conditions
Phenological matching
Carnivore production
Herbivore production
Plant production
Early Late Early Late Early
Late
Spring Summer Fall
(c) Climate-altered conditions
Phenological mismatching
Carnivore production
Herbivore production
Plant production
Early Late Early Late Early
Late
Spring Summer Fall

Figure 2 Depiction of a cyclic natural economy in which production by species lower in the food web (e.g., plants) supports production of species like herbivores and carnivores higher up in the food web. (a) All species in a food web take up nutrients and convert them into production. Species return nutrients back to the soil through waste elimination or carcasses. (b) Under normal conditions, the timing of production and nutrient recycling among the levels of the food web are synchronized among the seasons (phenological matching), so that species in upper levels of the food web can take optimal advantage of production of their prey. (c) Climate change can disrupt the synchrony in timing (phenological mismatch) leading to loss of production in the upper part of the food web. The amount of production lost (darkly shaded gray) increases with the degree of phenological mismatching. Humans rely heavily on herbivore species (meat production) and on carnivore species (fisheries) whose production stands to be jeopardized by climate change.

explained by among year variability in weather patterns (Voight et al. 2003). Species sensitivity to these patterns was measured as the amount of among year variation in species abundance that could be explained by among year variation in weather. This is a useful index because high interannual variability in species abundance means that a species' functional role in an ecosystem becomes less reliable than when the species varies less (Voight et al. 2003). The study revealed that plant abundance was comparatively insensitive to climate and that sensitivity increased as one progressed to species higher up in the food web. Weather patterns explained 1.4–1.8 times more variation in herbivore abundances than plant abundances; and 1.6–2.3 times more variation in predator abundances than plant abundances. Variability in species abundances may arise in this case because of phenological mismatch.

4.17.3.2 Phenological Mismatch and Dissolution of Feeding Dependencies

Phenology, or annual timing and progression of species' lifecycles, is synchronized across food webs. For example, temperate forest birds time their spring migration arrivals and their mating as closely as possible to peak hatching times of their insect prey, such as caterpillars in forest canopies, in order to provide ample food for their nestlings (Both et al. 2009). Hatching of caterpillars is timed to coincide with forest tree bud burst and leaf development because fresh, new leaves are nutritionally superior to older leaves. Spring temperature is an important cue that triggers this chain of events. Any changes in such climate metrics could change the timing of these life-cycle events. The change in timing would not be problematic if species could maintain their synchrony. Instead, we are seeing increasing asynchrony that is leading to a mismatch between species and their food – hence phenological mismatch – that is exacerbated as one moves to species higher up in the food web. Long-term study of a European forest ecosystem revealed that caterpillars seem to have adjusted quickly to the progressive 20-day advance in spring bud burst over the last 20 years. Songbirds that rely on these caterpillars have also adjusted the timing of their breeding activities, but only by about 10 days. Sparrow hawks that prey on songbirds have been unable to keep pace with the changes in their songbird prey's life-cycle development. This asynchrony in timing of life-cycle events between the species means that the predator species is less able to take advantage of peak abundances of its prey. This in turn translates into decreased ability of the predator to provision its young during the breeding period, naturally leading to lowered offspring survivorship and population viability. This case example is not an isolated incident. Empirical synthesis of data on over 3000 terrestrial plant and animal species in the United Kingdom have revealed that in 30% of the cases, plant phenology has advanced by 6 days over the last 30 years, which is twice as much as herbivore and predator species (Thakeray et al. 2010).

4.17.3.3 Loss of Ecosystem Regulatory Capacity and Potential for Regime Shifts

Ecosystem models that do not consider food web interactions often predict that higher atmospheric CO_2 levels and temperature increases can enhance plant production, assuming water and nutrients such as nitrogen and phosphorus are not in limiting supply. The classic bottom-up view of ecosystem functioning would then predict that enhanced primary production should enhance the abundance of herbivore and predator species. However, evidence from field experiments spanning 15 years during which mean summer temperature varied by 2 °C and mean monthly precipitation ranged from 2.5 to 5 cm shows otherwise. Each year, experimentation systematically manipulated the food web composition of herbaceous plants, insect herbivores, and spider predators in a grassland ecosystem specifically to resolve and quantify the strength of bottom-up and top-down control in this grassland ecosystem (Barton et al. 2009). This research revealed that plant productivity was unaffected by temperature change or precipitation, but the strength of top-down feedback increased by 30–40% for every 1 °C rise in temperature. This again reinforces that there is asymmetry in the degree to which bottom-up and top-down effects penetrate food webs. This asymmetry arises in part because herbivore consumption rates of plants may increase with temperature, due to elevated metabolic demands for nutrients in warmer environments (especially for insects), and warming temperatures lessen the physiological constrains on daily feeding activity of vertebrate and invertebrate herbivores. Further evidence from a variety of invertebrate herbivore species shows the amount of plant biomass consumed can double with every 1 °C rise in temperature (Watt 1995; O'Connor 2009).

Forty years of annual data indicate that a cyclic weather phenomenon with a decadal trend in temperature, moisture, and winter snowfall – the North Atlantic Oscillation (NAO) – has a strong influence on the structure and functioning of a northern forest ecosystem comprised of wolves, moose, and balsam fir on Isle Royale, Michigan (Post et al. 1999). These changes in temperature and precipitation influence food web dynamics in ways that one might expect under a climate-altered world (Schmitz et al. 2003). For example, during part of the 10-year cycle, NAO forcing results in winters with anomalously warm temperatures and little snowfall – conditions expected and climate warming; while other periods are closer to the average current climate. Examining long-term dynamics over four, 10-year cycles provide a window into how longer term increases in temperature and reduction of snowfall might alter northern forest ecosystem functioning and services through alteration of food web interactions.

The study revealed that whenever snowfall levels are high (as in current conditions), wolves are extremely efficient predators of moose that are encumbered by deep snow. Consequently, wolves reduce moose populations to levels where they cause limited damage to balsam fir (Post et al. 1999). Thus, wolves exert important indirect top-down control over the compositional make up of forest vegetation through direct interactions with moose. The role of wolves becomes diminished when NAO forcing causes snowfall levels to decline, because it decreases the moose capture efficiency of wolves (Post et al. 1999). Over the long term, temperature increases and snowfall reductions could cause a cascade of effects including declining wolf populations, rising moose populations, and declining balsam fir productivity. Moreover, moose may increasingly suppress sapling tree recruitment, resulting in a more open forest canopy with a changed understory of shrub and herb species. Studies of moose-vegetation dynamics in other boreal forest systems indicate that browsing-induced reduction of canopy height and closure by even 12–50% results in higher light intensity, lower humidity, warmer and drier soils, and lower primary productivity of tree species (Schmitz et al. 2003). Thus, if moose are able to increase to such high abundances that the capacity of top predators to control prey abundances becomes severally diminished, the entire system may undergo a regime shift to a state of chronically low balsam fir abundance in the face of high moose abundance (Schmitz et al. 2003). Over the long term, bottom-up control can become increasingly dominant, such that soil chemistry can become altered through reductions in litter quality and rate of litter decomposition, causing a buildup of soil carbon that feeds from the bottom-up to exacerbate the reduction in ecosystem productivity (Schmitz et al. 2003).

Additional studies in this Isle Royale system support the idea that climate can induce ecosystem state changes through regime shifts. When disease struck and decimated the wolf population, moose were released from strong control by wolves (Wilmers et al. 2006). As a consequence, two factors, climate and abundance of fir trees, accounted for 60% of the variation in moose population abundance. In contrast, these two factors only accounted for 25% of variation in moose abundance before the disease outbreak and wolves accounted for 35% of the variation. Thus, viable populations of top predators in this system can help to buffer the effects of long-term alterations of weather patterns on ecosystem functioning. Ironically, however, persistent and chronic warming could disproportionately affect the very species that buffer the climate effects. Such is an example, both of the brittleness of the ecosystem service provided by predators and a critical tipping point that can lead to sweeping changes at the whole ecosystem scale akin to the grassland ecosystem example presented above.

4.17.3.4 Rewiring Food Web Networks due to Change in the Nature of Species Interactions

Food webs can become rewired when the lines of feeding dependency between species become fundamentally altered. This rewiring can trigger community disassembly leading to the loss of species; or it can cause reassembly in which species change their functional role in ecosystems. Thus, how climate may affect food web networks depends on whether it triggers disassembly or reassembly processes.

An example of climate-caused community disassembly comes from research in a grassland food web composed of herbaceous plants, a grasshopper insect herbivore, and spider predators which revealed that two different kinds of predators, a sit-and-wait ambush spider and an actively hunting spider, may have altered use of habitat, as well as change the nature of their interactions in response to alterations in the climate they live in (Barton and Schmitz 2009). The two predators normally segregate vertically in the vegetation canopy. The behaviorally dominant sit-and-wait spider resides in the upper canopy and the subordinate jumping spider resides in the middle to lower canopy. Grasshoppers roam widely throughout the canopy in search of food during the course of their daily activity, and so must run the gauntlet created by both spider species. Consequently, the level of mortality experienced by the grasshopper population is the average of the individual spider species effects. This averaging direct effect of the spider species on their shared prey results in an averaging indirect effect on the plant community composition, as well as, on ecosystem functions like nitrogen cycling and plant production. Experimentally, increasing the temperature of this system causes the sit-and-wait spider to move lower down in the canopy where it is cooler, causing it to overlap more with the jumping spider. This overlap, results in fierce interactions between the two spider species and ultimately the extinction of the jumping spider population in the experimental system due to predation by the sit-and-wait spider (a phenomenon known as intraguild predation) (Barton and Schmitz 2009). Community disassembly, due to the loss of the jumping spider predator species from the food web, can have ripple effects by transforming the composition and abundance of plant species in the food web, and in turn, affecting ecosystem functioning including a 30% decline in nitrogen mineralization rate and a 35% decline an aboveground plant primary productivity (Schmitz 2009).

Climate-caused community reassembly can also arise, if an introduced species changes the nature of species interactions among the existing members of the food web. A case in point concerns the reintroduction of wolves in Yellowstone National Park, United States, which, in turn, enhances the resilience of the ecosystem to changes in the park's temperatures. Prior to wolf introductions, species of scavengers including coyotes, wolves, ravens, hawks, and nine other species were subject to the vagaries of yearly variation in weather caused by ENSO events (Wilmers and Getz 2004; Wilmers and Post 2006). In particular, carrion is widely available during ENSO phases that lead to deep snow, and hence, heavy winter mortality of prey species such as elk. ENSO can result in regional increases in temperature and less snowfall, thereby reducing lowers winter prey mortality. Thus, carrion for scavengers, particularly those with strong seasonal patterns in resource use, like grizzly bears, is reduced (Wilmers and Getz 2004). This, in turn, affects the viability and abundance of the scavenger species. The insertion of the wolf into the food web via reintroduction seemed to have enhanced the resilience of the food web by buffering the ENSO effects. Wolves are able to hunt year-round. The establishment of a predator–prey feeding link between wolves and prey like elk meant that there would be a steady supply of carrion to the scavenger species among seasons and years. Wolves may increase the resilience of this ecosystem by causing a crucial food resource in the food web to be controlled by a more constant biotic rather than variable abiotic factor Wilmers and Getz 2004; Wilmers and Post 2006).

4.17.4 Possibilities for Climate Effects to Alter Ecosystem Function

The case examples presented here were chosen because they offer solid evidence for the kinds of ecosystem effects that can be realized through climate effects on food webs. The scientific evidence comes from two kinds of sources: observational studies that track interannual variation in abiotic conditions (temperature, precipitation, etc.) and manipulative experiments that alter abiotic conditions. The experimental studies often push abiotic conditions to a 3–5 °C rise in the temperatures experienced by the study area, which is felt to be a plausible possibility in the coming decades. This portends future community disassembly that could cause regime shifts and significant (e.g., 30–40%) reductions in levels of ecosystem functioning and services. These effects come about because top predator species are important determinants of ecosystem resilience to climate, but at the same time, are the species most sensitive to human impacts on food webs through resource exploitation.

These examples highlight the potential for the functional role of upper level species (especially predators) to be more brittle (less resilient) than that of species (e.g., plants) lower down in the food web. In many cases, the implications of climate effects on terrestrial food web interactions have yet to be empirically traced to ecosystem functioning. Thus, it remains altogether uncertain what effects predator loss will have on production of natural resources in ecosystems in the future.

The current inability to assess the likelihood of the different kinds of outcome illustrated above arises from two limitations with our scientific understanding. First, empirical case studies are insufficient in number to conduct meta-analyses that assess likelihoods of outcome. Second, the reliability of estimated future conditions using food web and ecosystem models is heavily dependent on accurate understanding of biological conditions that form model assumptions, as well as accurate estimates of parameters that drive the model dynamics, including how well climate models can predict the spectrum of possible future local and regional climate. Again, our empirical understanding of the range of climate effects on food webs and ecosystems is insufficient to constrain the range of model parameter values. Thus, it is impossible at this time to offer general conclusions.

4.17.5 Policy Actions to Minimize or Eliminate the Negative Consequences of Climate Effects

The scientific community has amply demonstrated that changes in local and regional climate statistics could reorganize communities and associated ecological systems across landscapes because species existing within a community would not respond in the same way to this stressor. Some species may tolerate the climate stressor. Others may shift their geographic ranges, but, nevertheless, may not move en masse to new locations, leading to community disassembly. Moreover, new species migrating from other regions may enter a food web and forge new dependencies with the local species leading to community reassembly. Yet, much of the focus in natural resource conservation and management is still on single species or single resource stocks that have particular value for stakeholder groups.

A practical start to addressing climate effects on food webs and ecosystems is to begin recognizing that the processes of community disassembly and reassembly means that focusing on single species or resources when planning for climate adaptation will provide incomplete solutions (**Figure 1**). The scientific lessons presented here are that conservation and management must take a broader food web perspective and change its conception of the important factors controlling ecosystem functioning. A food web perspective highlights that species do not exist in isolation but rather belong to larger communities based on common habitat, resource, and thermal needs. It then logically follows that species in ecosystems may not simply be a product of available production within an ecological system (bottom-up control), but may also be integral and active players determining how the ecological systems function (top-down control). This perspective embraces modern scientific understanding about species' functional roles in nature. Moreover, a food web perspective can help reason through how important dependencies among species might become uncoupled, as well as understand the potential fate of species that are important to the provision of ecological services. Species within food webs are interdependent with each other and may provide important ecological services because of those interdependencies, not in isolation of them (**Figure 1**).

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4.18 The Vulnerability of Tourism and Recreation to Climate Change

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4.18.1 Introduction: Scope and Scale

Tourism is an ambiguous term that refers both to a commercial industry and to a category of human behavior, with all the associated psychological, social, and economic incentives and constraints. From the industry perspective, which includes government tourism portfolios and economic statistics agencies, tourism is generally defined as overnight travel more than 40 km from home, for purposes which are personal rather than work-related. This is a definition of convenience that includes some rather blurred and arbitrary boundaries, but it is useful for statistical purposes. From a social perspective, any individual's time can broadly be divided into work, home, and play, i.e., employment, domestic, and leisure. Recreation is one component of leisure, and tourism is a type of recreation that involves travel.

In practice, tourism usually involves the purchase of commercially provided products specifically for that particular holiday journey. Such products are generally divided for convenience into transport, accommodation, and activities. A family that drives 100 km in its own car, camps overnight in its own tent, and eats food that it brought from home would probably think of this activity as recreation rather than tourism, but would nonetheless technically be treated as tourists in statistical terms. Similarly, many recreational activities, commercial or otherwise, are available to and equally enjoyed by locals and visitors alike. Examples include hiking in a national park, surfing or sunbathing at the beach, or going as a spectator to a musical or sporting event.

Estimates of the economic scale and social significance of tourism and recreation thus depend on just what is included. International tourist air travel, for example, is routinely recorded with reasonable precision, and aggregate figures are compiled and annually published by the UN World Tourism Organization (UNWTO). In many countries, however, domestic tourism is far larger in scale than international: up to two orders of magnitude larger, for example, in countries such as China and India. In addition, the relative scale of domestic and international tourism depends on the size of the countries concerned. A distance that represents an international journey in Europe, Central America, or Southeast Asia would be domestic travel in the United States or Russia. Ignoring these statistical distortions, UNWTO (2011) reported almost one billion international tourist arrivals in 2010, representing an annual expenditure of close to one trillion dollars.

The economic scale of domestic tourism and recreation is more difficult to gauge accurately. Fully packaged tours, which include the costs of labor, catering and consumables, and recreational equipment rental as well as transport and accommodation, make up only a small proportion of total domestic travel, generally less than 15%. For the remainder, people use the same vehicles that they also use at work and at home, they use the same recreational equipment that they may also use after work or at the weekends, and they rely on their own labor rather than paying anyone else. They may stay in a relative's house, a holiday house, or a second home. Whether this involves walking from one mud hut to another or taking a private helicopter to a palace, it rarely involves commercial transactions that can be tracked by economic statisticians.

Instead, economic estimates for these components involve partitioning the size and scale of the sporting goods market, the property market, and the automobile market, and assigning a value to individual unpaid time. As in all industry sectors, there is also an economic multiplier effect in tourism-dependent communities, as people employed in the tourism sector locally spend their earnings. Taking these factors into account, the World Travel and Tourism Council (WTTC), tourism's peak international industry association, estimates the global economic scale of tourism as USD seven trillion, almost an order of magnitude higher than the UNWTO estimate. Estimates from other sources indicate that outdoor recreation in the United States alone is worth USD 852 billion, approaching the trillion-dollar estimate provided by UNWTO for the entire international tourism sector.

Perhaps more important than the absolute economic scale of the tourism sector is its position relative to other sources of revenue, in particular countries and communities. Worldwide, tourism is estimated to contribute 9.1% of global Gross National Product (GNP), and >10% of global employment (WTTC 2011). Similar figures apply at national scale for large and wealthy developed nations with mixed economies. For a number of smaller nations, however, particularly in the developing world, tourism is a much more significant economic sector.

In particular, there are at least 50 nations where tourism provides the largest single source of foreign exchange, essential if governments need to purchase equipment not locally available or if companies need raw materials not available in the country concerned. Commercial tourism, particularly international tourism, has thus become a significant contributor to economic well-being in a number of countries and rural communities; but equally, this dependence makes them vulnerable to any disturbance or downturn in inbound visitation rates. Of course, such international dependencies are by no means restricted to the tourism industry. They do, however, add an extra complexity in calculating the vulnerability of tourism and recreation to climate change.

4.18.2 Components and Sources of Vulnerability

In examining the vulnerability of tourism and recreation to climate change, we can consider three distinct though tightly cross-linked components. The first is the tourists, that is, the people who plan to play, whether close to home or far away. The second is the destinations: the places they want to visit. The third is the enterprises, the many tourism-related businesses that help to get the tourists to their destinations and look after them once they arrive.

Changes to any one of these components will commonly also affect the others. If a destination becomes relatively more or less attractive to tourists, because of local effects of climate change, that will influence the number of tourists arriving there, unless the various enterprises involved can successfully market different or changed attractions at the same destination. If people from a particular country or region travel more or less because the climate at home has changed, that will affect the destinations they travel to and the enterprises they travel with. If the cost of a particular travel-related service increases because of climate-related effects, and fewer tourists purchase that service as a result, then the enterprise providing the service may change what it has to offer, with consequences for tourists, destinations, and other enterprises.

In examining the vulnerability of tourism and recreation to climate change, therefore, we need to consider all three of these components and also the links between them. We start by examining direct physical effects of climate change on tourist destinations, and the degree to which these can be counteracted by engineering approaches, exacerbated by changes in social institutions, or outweighed by changes in tourism product portfolios and marketing strategies. Next, we consider the various factors that influence when, where, and how much individual tourists travel, and how these will be affected by climate change. Finally, we consider how tourism enterprises can adapt to such changes in tourist behavior, and how changes in tourist behavior and destination attractiveness will affect different subsectors of the commercial tourism industry.

Like most industry sectors, tourism contributes *pro rata* to greenhouse emissions and consequent climate change, particularly through longhaul air travel. Like most primary industry sectors, but unlike most secondary and tertiary sectors, the tourism industry is also highly vulnerable to the impacts of climate change. As outlined above, this includes both direct physical changes at tourist destinations and recreational sites, and indirect changes in travel and activity patterns caused by the increasing financial and possibly also social costs of holiday travel. In line with the theme of this volume, this chapter examines only how tourism and recreation are affected by climate change, not how they may contribute to it.

4.18.3 Destinations

Even at a global scale, predictions of key climatic parameters, such as temperature, rainfall, sea level, and so on, still remain somewhat uncertain (IPCC 2007; Parmesan and Yohe 2003). At the regional and local level relevant to tourism and recreation, there are few fine-scale predictions for critical parameters, and most of these indicate high levels of uncertainty. Early models, for example, predicted increased storminess for the tropical east coast of Australia, whereas more recent models predict less storminess but a more acid ocean with impacts on coral reefs (Hoegh-Guldberg et al. 2007). In addition, predictions are that in many regions, several climatic parameters will change simultaneously. Many montane areas, for example, are expected to experience increased temperatures coupled with reduced rainfall, and both of these reduce snow cover (Pickering and Buckley 2010). Reduced snowfall, especially at lower altitudes, affects ski tourism destinations in many countries (Scott and Seiger 2013; Agrawala 2007; König and Abegg 1997).

Especially where several primary climate parameters change simultaneously, these changes can generate a chain of secondary consequences. In woodland areas, for example, a combination of raised temperatures and reduced rainfall is likely to increase the frequency and intensity of fires (Buckley 2007) and may extend the length of the fire season (Lucas et al. 2007). In low-lying coastal areas, more intense low-pressure weather systems could create both heavier rainfall and increased storm surge due to low atmospheric pressure, producing more widespread flooding in urban areas and increased erosion on some rural coastlines (Buckley 2007).

Commercial tourism development, especially at large scale, also needs large volumes of water. In many countries, water supplies are already limited and subject to intense competition from other industry sectors. If rainfall decreases or becomes more irregular, or temperature and evaporation increase, or both, then water availability will decrease and water prices will increase. This is already the case for many of the world's coastal tourism destinations.

Changes in seasonal and diurnal temperature patterns in rainfall and groundwater, and in fire and flood regimes, can all influence vegetation and wildlife (Klanderud 2005). Indeed, the geographic distribution and annual life histories have already changed in response to climate change for many hundreds of plant and animal species (Root et al. 2003). Any change for any one species, either in space or time, can have consequent impacts on others.

These patterns are commonly quite complex and difficult to predict. Many species exist in balance not only with their physical environments, but with each other. They may compete for space or resources, or rely on each other for food or dispersal. Under such circumstances, even quite a small change in the climatic, physical, or biological context for such interactions between species can generate a greatly amplified response. Long-term ecological research has shown that the boundaries of adjacent patches of different vegetation can move back and forth over time as they compete for space, with the relative advantage depending on weather patterns. Under climate change, the historical balance may be permanently altered in favor of one or other of these plants. This affects all the associated plant and animal species, including those significant for commercial tourism.

As another example, many species of birds worldwide time their nesting periods to coincide with a large-scale spring emergence of insects, which they use to feed their nestlings. There are already a number of cases where, as a result of climate change, the insects have hatched earlier in the year (Roques and Robinet 2010) and the birds have gone hungry. Once again, given the increasing economic scale of the birdwatching tourism sector worldwide, anything that changes the opportunities for tourists to see particular species may have economic and social as well as environmental consequences.

Further complexities and consequences arise because of the interactions between physical and biological changes, and human social factors. This includes both individual human behavior, and social structures and institutions such as land tenure and land use patterns, taxation systems, and travel patterns. For example, if tourists have historically been able to watch individual icon wildlife species in particular national or marine parks, either year round or seasonally, but because of climate change those species no longer survive or migrate there, that will affect any commercial tourism product based on seeing those species. Such concerns are particularly well-known for polar bears, notably for the bear-watching industry of Hudson Bay in Canada (Stirling and Parkinson 2006; Dawson et al. 2010), but they may equally apply to many other species.

Similarly, if land management agencies close access to particular areas because of increased fire or flood risk, and/or open access to new areas, then those changes will affect any tourism enterprises whose products rely on such access. Agencies may also allow continued access for some purposes, but place restrictions on particular activities that were previously permitted. This applies to public lands such as national parks and forests and also to private land, and it has already occurred in some regions. Kosciuszko National Park in Australia provides an example.

There may also be indirect social changes at destinations. If reduced or increased attractiveness or access changes demand or availability at particular destinations, affecting the number of visitors arriving, then this may also affect the attitudes of residents to tourists, and the prices and availability of tourist services and infrastructure offered.

4.18.4 Tourists

Changes at destinations modify their attractiveness to tourists, also known as the 'pull' factor. Climates are also simultaneously changing in tourists' countries of origin. Tourism is driven in part by the attractiveness of a holiday destination relative to home. Changes at home, the 'push' factor, can thus also alter this balance (Crowe 1975; Bigano et al. 2006; Hamilton and Lau 2005; Lise and Tol 2003; Eugenio-Martin and Campos-Soria 2010; Hall and Higham 2005).

The most critical climate changes are those that affect the least attractive season at home. If cold-country winters get colder or hot-country summers more (or less) humid, for example, that influences what residents do for leisure and recreation both locally and by traveling. They may shorten or lengthen the season for particular recreational activities, or add or substitute different activities; or they may travel more, or less, or to different places for either the same or different types of leisure and recreation (Wall 1992). All of these preferences and behaviors may differ between different ethnicities, socioeconomic statuses, and individual backgrounds.

In addition to changes in both push and pull factors for people to travel as tourists from and to particular places, their travel decisions are also influenced by the cost and convenience of transport options (Tol 2007; Peeters and Dubois 2010; Buckley 2011a). Demand for holiday travel is currently quite inelastic to price (Tol 2007; Buckley 2011a,b); but as carbon taxes or tradeable permit systems, coupled with rising fuel price, increase air travel costs, people may change the pattern, distance, frequency, or mode of holiday travel. This, however, depends on availability. People can only switch from plane to train if trains actually exist. And if people want to bring bicycles instead of hiring cars at their destination, they can only do so if the plane or train makes this simple and cheap (Dickinson et al. 2010, 2011).

It is also possible that travel patterns may be changed through social pressures as well as prices. To date there is little evidence of this: people continue to travel on holiday, even if they are aware of their climate change impacts; and they provide various social justifications for doing so (Buckley 2011a,b; Dickinson et al. 2010, 2011; Gössling et al. 2007; Dawson et al. 2010; Becken 2007). Some tourist destinations aim to counteract any negative social perceptions of longhaul travel through large-scale carbon offset programs, so as to become 'carbon neutral' (Gössling and Schumacher 2010). These programs have limited credibility at present (Gössling et al. 2007; Anderson 2012; Edwards et al. 2011).

These factors may or may not change as the world's wealth shifts between nations. Currently, a high proportion of long-haul air travel is attributable to a relatively small number of so-called hypermobile travelers, mainly from North America and Europe. As citizens of the BRIC nations – Brazil, Russia, India and China – become increasingly wealthy and want to travel more, it will be their social attitudes that influence travel patterns. These are less studied and are rapidly changing.

4.18.5 Enterprises

The ways in which individual commercial tourism enterprises are likely to be affected by climate change, and the ways in which they can adapt, depend strongly on the types, structures, and locations of the enterprises concerned. Companies that act principally as packagers or agents, whether outbound or inbound, are likely to be least affected. If particular destinations or activities become less attractive to tourists as a result of climate change, these companies can simply substitute alternative places and products, and so continue to retain or expand their client base.

The same applies for companies that offer a single activity at many different destinations. Different degrees of change may be needed, depending on the type of activity offered. Activities that take place in urban or other man-made environments, such as golf courses, will probably continue to operate unabated at the same locations as currently; though costs may increase or decrease to reflect the changing prices of, for example energy and water.

For activities that rely on a natural attraction in a built or urbanized setting, such as ski and beach resorts, engineering adaptation to climate change is feasible in the short term (GBRMPA 2009; Hallegatte et al. 2011). In the medium term, factors such as reduced snowfalls or water supply, rising sea levels, or increasing incidence of disease, are likely to make particular destinations relatively more or less attractive in the future (Buckley 2008a,b; Scott and Seiger 2013).

For destinations that are already large and well-known, substitution between activities is also possible, for example, from winter skiing to summer golf, or from ocean bathing to swimming pools. For activities that are completely dependent on the natural environment, such as whale watching or whitewater rafting, sea kayaking or game safaris, a much greater degree of substitution may be required, since particular attractions or activities may become completely unavailable in some areas that were previously popular.

Tourism enterprises that offer only a single activity at a single destination are potentially most vulnerable to climate change; though again, vulnerability may greatly differ between destinations and activities. If melting of the Arctic sea ice means that polar bears no longer visit Hudson Bay in northern Canada, for example, then the companies that currently offer tours to watch them from the heated giant-wheeled buses known as tundra buggies, will completely lose their clientele. On the other hand, the same melting of Arctic sea ice makes new areas accessible to cruise ships.

Likewise, if the increasing risk of summer bushfires in the dry eucalypt forests of Australia's Snowy Mountains means that the park management agency restricts overnight camping during the summer months, then a local farm that offers multiday horse riding tours into the park, with overnight camps and campfires in 'The Man from Snowy River' style (Ollenburg 2006), might still have clients but nowhere to take them. A company that offers artistic or retail attractions at an urban venue, however, is likely to be little affected by climate change as long as tourists still visit the town concerned.

Tourist enterprises are in any event constantly adapting and readapting to match the interests of potential clients to the possibilities of particular destinations. They will feel the effects of climate change both through changes at destinations, as outlined above, and through changes in the behavior of individual tourists. These are very difficult to predict because they involve the interaction of several quite different factors.

Changes in the features of particular destinations and products on offer, as outlined above, do not operate independently. There are also changes in climate at major countries of origin, which affect the relative attractiveness of different potential ways to spend one's vacation time. There may be quite large-scale changes in the financial costs and social context for holiday travel, especially longhaul international air travel. In addition, travel patterns are heavily dependent on the relative distribution of wealth, on cultural differences between countries, and on the ever-fickle effects of fashion. All of these overlay, and may outweigh, the effects of climate change, so that the latter are difficult to detect reliably.

4.18.6 Most Vulnerable Subsectors

The ski industry is particularly vulnerable to warming and to reduced precipitation, since these changes reduce both natural snow cover and opportunities for snow making. Ski resorts in North America and Europe, Australia, and New Zealand are much more vulnerable than those of Hokkaido in Japan or those of northern Canada and Alaska (Agrawala 2007; König and Abegg 1997; Scott and Seiger 2013). The industry's response to date has been to increase snow making, snow grooming, and terrain modification; to reposition resorts from winter to four-season; and to increase financial reliance on property and retail rather than lift tickets (Pickering and Buckley, 2010).

The coastal resort industry has responded to climate change much more slowly than ski resorts (Buckley 2008a). Possible reasons include lags in oceanic as compared to atmospheric changes; more distributed ownership of land and infrastructure in coastal settlements; controversy over liabilities and responsibilities; and misperceptions of likely climatic impacts (Buckley 2008a). Tourists seem to be more concerned with esthetic appearance, whether natural or man-made, than with erosion or coastal processes *per se* (Buckley 2008a; Moreno and Becken 2009; Buzinde et al. 2010).

Tropical coral reefs are susceptible to bleaching from warm ocean temperatures (Burke et al. 2011), but to date this seems to have had relatively little effect on tourism (Lasagna et al. 2010). Many of the world's reef tourism destinations have experienced bleaching events, but the only serious effect on visitation so far seems to have been a 9% drop at Palau (Glantz 2000, cited in Becken and Hay 2007). Experienced divers descend below the impacts of bleaching, and snorkellers seem unconcerned as long as they can still see fish. Future effects may be more severe if the ocean becomes increasingly acid (Hoegh-Guldberg et al. 2007).

Low-elevation tropical and subtropical oceanic island destinations are especially vulnerable to sea level rise, increased storminess, degradation of coral reefs, and increased costs of longhaul air travel. To date, there has been limited impact on tourism revenue, since these destinations have simply adopted more heavily engineered forms of development, which they were moving toward in any event so as to increase capacity, safety, and levels of luxury.

Higher-elevation bedrock islands, whether at high or low latitudes, are less concerned over physical changes and more over potential losses in visitation due to increased travel costs. The Azores, for example, has complained that European Union carbon taxes on air travel are affecting its tourism economy. The Seychelles has claimed that it will reposition itself as a 'carbon neutral' destination, but this seems likely to be merely a marketing claim designed to assuage the consciences of its wealthy international visitors.

In forested destinations, the main risks of climate change are from increased wildfires, which damage infrastructure and affect both access and attractiveness for tourism. In grasslands and deserts, droughts will affect populations and migrations of icon watchable wildlife species, as well as grazing pressure from domestic livestock, cultural landscapes, and the availability of water. None of these have yet been analyzed at significant scale and detail from a tourism perspective.

4.18.7 Priorities for Future Research

Three major themes are immediately apparent as priorities for future research to assess and minimize the vulnerability of tourism and recreation under climate change.

The first theme principally applies to urban tourist destinations and large-scale resorts. For these, the key issue is the degree to which market share can be maintained by modifying the mix of activities and attractions. This is essentially a question of tourist behavior, and there is already a considerable body of academic literature on tourism economics and geography, marketing and market research, and destination lifecycles that could be adapted to examine this question.

The second major theme is that of extreme weather events: their immediate impacts on tourist safety, attractions, and infrastructure, and their longer-term effects on competition between destinations. There is already a significant academic literature on disaster response and crisis management in tourism, which can be applied here.

The third, and perhaps most complex research theme, is in predicting how natural attractions for tourism may be modified by climate change and how tourists may change their travel patterns accordingly. This theme covers not only direct impacts of climate change on parks and beaches, water and wildlife, but also the indirect impacts on tourism as the social frameworks for access to these attractions change in response to changing climates (Buckley 2007).

4.18.8 Conclusions

Climate change is indeed a highly significant issue for the global tourism industry: less acute than wars and terrorism, but larger scale and longer lasting. The subsectors of the tourism industry most affected by climate change will be smaller fixed-site operators or destinations that heavily rely on a single natural attraction, such as snow, reefs, or wildlife, that happen to be particularly susceptible to climate change. Even in these cases, however, there are opportunities to reposition either the product or the target market segment so as to maintain revenue. The key in these cases will be forethought and innovation to maintain a competitive position as corresponding adjustments occur worldwide.

Climate change is likely to become so pervasive that it should be mainstreamed into all aspects of tourism research. To some degree, this has already happened (Hall 2008; Hall et al. 2011; Schott 2010; Scott et al. 2007; Weaver 2011; Scott and Seiger 2013). Already, many analyses in tourism economics routinely refer to various climate change scenarios in much the same way as they routinely specify discount rates. Future research in tourism planning, policy, and geography will no doubt refer to regional climate change patterns and predictions in a similar way.

In the short term, however, it would seem that if we were to pick a single top priority for research, it would be the social and environmental consequences of extreme weather events at destinations, and the flow-on effects for tourism.

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4.19 Assessing Cumulative Risks to Ecosystem Function: Expectations and Realities of Environmental Change Interaction Effects

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4.19.1 Introduction

The world is currently experiencing a suite of environmental changes (see Section 4.19.2, this volume), which are causing rapid declines in biodiversity. In addition to the moral tragedy of this loss, there is growing concern that biodiversity loss may negatively affect the way in which ecosystems function, and the services that these functions provide. Since a number of seminal studies in the early to mid-1990s (e.g., Naeem et al. 1994; Tilman and Downing 1994; McGrady-Steed et al. 1997), there has been a growing consensus that biodiversity is generally important for the maintenance and stability of ecosystem functioning (Chapin et al. 2000; Hooper et al. 2005; Díaz et al. 2006), though there are a number of case studies showing no effect, or even a negative effect of biodiversity on the rates of certain ecosystem functions or processes (Rodriguez and Hawkins 2000; Finke and Denno 2004; Srivastava and Vellend 2005). Therefore, rather than simply asking 'does biodiversity affect ecosystem functioning', understanding the context under which biodiversity is important has become a major issue, which we will discuss below. Biodiversity effects will also occur within the context of direct effects of environmental changes on ecosystem functioning, and disentangling the relative importance of these pathways will be a major challenge for the future (Huston and McBride 2002). Therefore, we will discuss these direct versus indirect pathways, and how establishment of their relative impact may determine the most effective approach to managing ecosystem services in a changing environment, as well as the circumstances under which conservation of biodiversity will bear the greatest impact on ecosystem functioning.

Despite this uncertainty regarding the importance of biodiversity relative to the direct effects of environmental changes on ecosystem functioning, there is growing appreciation that multiple drivers may have non-additive impacts, such that the overall effects on ecosystems cannot be predicted from the effect of each driver in isolation. This is being increasingly (albeit slowly) recognized as important for biodiversity loss and threatened species management (Didham et al. 2007; Brook et al. 2008). However, the nonindependence of multiple drivers has not been well incorporated into the literature examining biodiversity effects on ecosystem functioning. The distinction is probably symptomatic of the disconnect between studies examining the causes of biodiversity loss, which increasingly recognize interactions among multiple drivers (Didham et al. 2007; Brook et al. 2008), and studies examining the consequences of reduced biodiversity, which usually simulate random species losses in experiments, without inferring any particular driver or drivers of this loss (Srivastava and Vellend 2005).

Nevertheless, real world extinctions are not random, but rather depend on characteristics (traits) of individual species (e.g., Lavorel et al. 1997; Lavorel and Garnier 2002; Larsen et al. 2005). Thus, individual drivers of global change may select for species with certain responses to a given stressor (e.g., 'response traits', Elmqvist et al. 2003), which may in turn be related to their contribution to ecosystem functioning (e.g., their 'effect' traits, (Lavorel and Garnier 2002; Larsen et al. 2005), Figure 1). We will discuss how environmental changes such as climate may select for certain functional traits, and how this may generate strong interactive effects on ecosystem functioning. Finally, we will draw overall conclusions about the cumulative threat to ecosystem functioning posed by a suite of environmental changes, and highlight areas in need of future research.

4.19.2 Direct and Indirect Effects of Environmental Change on Ecosystem Functioning

As mentioned above, there can be important indirect effects of environmental changes on ecosystem functioning, mediated through the loss of biodiversity (Figure 1, see also the chapter

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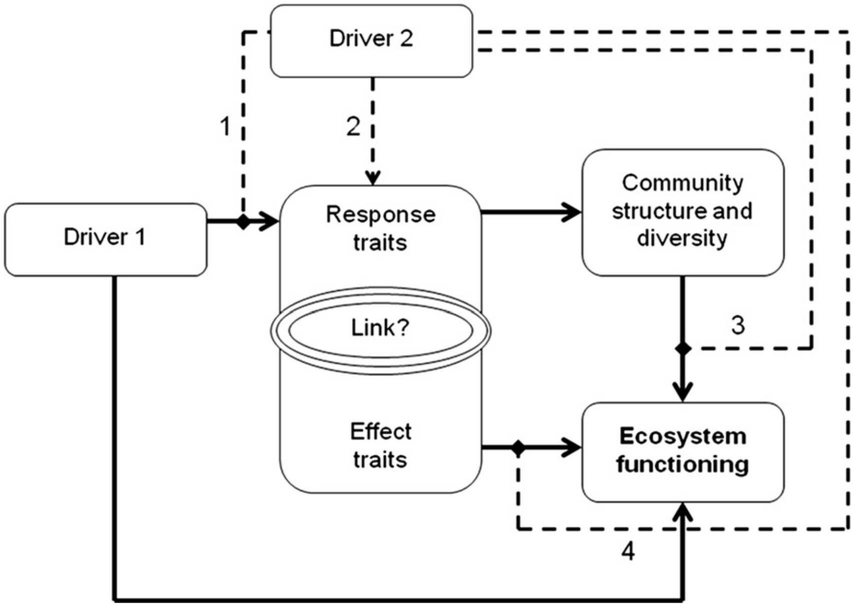

Figure 1 Direct and indirect pathways through which two drivers of environmental change can interactively affect ecosystem functioning. Arrows indicate direction of effect; dots within arrows indicate that the effect pathway is moderated by another driver. Solid lines indicate the direct and indirect effects of Driver 1, whereas dashed lines (paths 1–4) indicate the additional effects of Driver 2. The latter include **path 1**: Driver 2 changes the trait optima selected by Driver 1, **path 2**: Driver 2 selects for different trait optima, **path 3**: Driver 2 moderates the diversity–function relationship, **path 4**: Driver 2 moderates how specific trait combinations affect ecosystem functioning. In these cases, drivers could be weather-related variables (temperature, precipitation, heat waves), atmospheric composition and pollution (CO_2 concentration, nitrogen deposition), species invasions, or land-use change (fragmentation). Adapted from Figure 1(c) in Lavorel, S., and E. Garnier, 2002: Predicting changes in community composition and ecosystem functioning from plant traits: revisiting the holy grail. *Funct. Ecol.*, **16,** 545–556.

of Kittel, this volume). However, in addition to indirect biodiversity-mediated effects, all environmental changes may themselves have direct impacts on ecosystem functioning (Figure 1). For example, facets of agricultural intensification obviously have direct effects on functions such as biomass production (the ‘Green revolution’ of the mid-to late twentieth century demonstrated this comprehensively), and nitrogen deposition may enhance rates of decomposition (Manning et al. 2008). Even when species diversity is unaffected, changes in the abundance of a functionally important species may alter ecosystem process rates. For example, habitat fragmentation (both increased isolation from natural habitat and reduced area of habitat within the landscape) has been shown to reduce bumblebee abundance, which led to reduced pollination of tomato crops (Greenleaf and Kremen 2006). Thus, even in the absence of indirect biodiversity-mediated effects, environmental changes can impact ecosystem functioning directly.

That environmental changes have these kinds of direct effects on ecosystem functioning should come as no surprise. However, more surprising is the paucity of research addressing the relative importance of biodiversity loss (an indirect effect on ecosystem functioning) versus direct effects of the environment on functioning (Huston and McBride 2002), and how this relative importance may vary across systems. Importantly, this balance will determine the utility of different management approaches for maximizing ecosystem services. For example, if the effects of biodiversity loss on functioning are minute relative to the direct effects of these human impacts, then the functional argument for species conservation would be weakened.

Based on observations of natural patterns of productivity and species richness, it has been suggested that biodiversity can play only a minor role in functions such as primary productivity, which are instead driven primarily by environmental (abiotic) conditions (Huston 1994; Huston and McBride 2002). This tenet has recently been tested in a study that used a ‘response-effect trait framework’ (Lavorel and Garnier 2002; Suding et al. 2008; see below) and structural equation modeling to determine the direct and indirect effects of two components of land-use change (experimental fertilization and grazing intensity) on biodiversity and ecosystem functioning (Laliberté and Tylianakis 2012). After more than 20 years of simulated grazing and fertilization treatments, composition and diversity of the plant community had changed considerably, with consequences for several ecosystem functions. This work found that functional trait diversity in plant communities affected aboveground primary productivity, and that productivity was positively related to other ecosystem functions such as leaf decomposition and soil carbon sequestration (Laliberté and Tylianakis 2012). These results support the results of the previous biodiversity experiments (discussed above) that assume random species loss, and confirm the importance of primary productivity as an aggregate measure of community functioning. However, the effect of functional trait diversity on productivity only became positive under conditions of high soil resource availability; for example fertilization moderated the biodiversity effect (see next section). Most importantly, the direct effect of soil resources (and to a lesser extent of grazing intensity) on all the ecosystem functions measured was far greater than the indirect effects mediated via biodiversity loss or changes in the trait composition of the plant community (Laliberté and Tylianakis 2012).

This result is somewhat intuitive, as many of the most productive ecosystems on earth (e.g., agricultural crops, forestry plantations) have low biodiversity (Huston and McBride 2002), and it is the primary driver of this biodiversity loss (land-use intensification) that itself maintains the high rates of productivity. Thus, selection of species for agriculture that produce high yields, combined with external inputs such as nutrient fertilizers, has to an extent uncoupled biodiversity from ecosystem functioning in many anthropogenic systems. This may explain the apparent paradox that humanity is receiving increasing ecosystem services at the same time as biodiversity is declining (Raudsepp-Hearne et al. 2010), and emphasizes that functional degradation of ecosystems may be masked by external inputs that cannot necessarily be sustained in the long term.

These broad issues of the timescales over which biodiversity is important, and the long-term sustainability of functioning, must be incorporated into any assessment of the Earth's vulnerability to environmental change. In particular, the selection of certain kinds of species by one environmental change driver may affect the resilience of the system to other drivers (discussed below). Finally, the above work illustrates that we should not expect to see general patterns in the effects of biodiversity loss across all systems, but rather, we must understand the conditions under which biodiversity loss will have its greatest impact.

4.19.3 The Importance of Environmental Context for Biodiversity Effects on Functioning

In addition to the direct effects of environmental changes on ecosystem functioning, and the indirect effects mediated through biodiversity loss, environmental changes may even moderate the importance of biodiversity for ecosystem functioning (**Figure 1** pathway 3). One of the main mechanisms underpinning a positive biodiversity-ecosystem functioning relationship is niche complementarity (Loreau et al. 2001), whereby different species utilize different resources, or the same resources are obtained in different ways. This reduces interspecific competition relative to intraspecific competition, and allows more complete utilization of the available resources, thereby maximizing functioning at the community level. Clearly, for complementarity to operate, two requirements must be met. First, different species must occupy different niches or functional groups (Loreau et al. 2001; Wardle and Zackrisson 2005). Second, there must be a range of niches available to be partitioned among the species, or in other words, there must be a heterogeneous resource base (Tylianakis et al. 2008b).

The ecosystem function receiving the most attention in the literature, plant biomass production (possibly because of its link to ecosystem services such as carbon sequestration and pasture production, and because it can correlate with other functions, see above), provides a clear example of this phenomenon. Complementarity among plant nutrient acquisition strategies, which could potentially make diverse plant assemblages more productive, requires heterogeneity in resources such as soil nutrients. Differences in soil heterogeneity may therefore have blurred the effects of biodiversity in some experiments, and created contrasting experimental results across regions (Huston and McBride 2002).

The importance of soil nutrient heterogeneity for moderating biodiversity effects was tested explicitly in German grasslands, using structural equation modeling of observational data (Tylianakis et al. 2008b). It was found that plots with more heterogeneous soil resources had a stronger relationship (i.e., a more positive slope) between plant biodiversity and biomass production (belowground biomass in this case). It was argued that heterogeneous soil resources created a greater variety of niches to partition, which could be better exploited by diverse plant assemblages than by those that were species poor. This premise was supported by similar evidence from experimental studies (Weis et al. 2008). In addition to plant biomass production, results from Indonesia and Ecuador showed that the relationships between diversity (of pollinators or parasitoids, respectively) and functions (pollination success and host attack rates) also became stronger with increasing heterogeneity (patchiness) in the availability of the resource being partitioned (flowers and hosts, respectively) (Tylianakis et al. 2008b; Weis et al. 2008).

Finally, in addition to resource heterogeneity being important, the total amount of available resources may moderate the effect of biodiversity on ecosystem functioning. Of course, resource availability may alter rates of competitive exclusion, thereby determining local biodiversity in the first place (Huston 1994). However, experiments have shown that, like heterogeneity, resource availability may moderate the diversity–function relationship, which becomes increasingly positive as resource availability increases (Fridley 2002; Boyer et al. 2009; Laliberté and Tylianakis 2012). In terms of ecosystem services, Laliberte and Tylianakis (2012) note that these findings support the importance of diverse species mixtures for maximizing the efficiency of high-input production systems, such as pastures (Sanderson et al. 2004) or biofuel crops (Fargione et al. 2008).

Combined, these results suggest that environmental context (such as resource availability and heterogeneity) plays an important role in moderating the effect of biodiversity on ecosystem process rates, and this hypothesis can be applied to any ecosystem service for which biodiversity is important. For example, diverse predators (control agents) may improve the success of biological control (Snyder et al. 2006), though this benefit may only occur under certain circumstances (Tylianakis and Romo 2010). However, these results carry an even greater importance within the context of environmental change. For example, increased climatic variability may generate greater temporal heterogeneity in the availability of resources (such as prey for predators, or flowers for pollinators), which could make biodiversity more important for maintaining ecosystem functioning. In contrast, other environmental change drivers (such as land-use change or nitrogen deposition) may homogenize basal resources, potentially reducing the benefits of biodiversity, or increase resource abundance, with the opposite effect. Thus, any change can potentially have direct effects on ecosystem functioning, indirect effects mediated through biodiversity loss, and even potentially moderate the relationship between biodiversity and ecosystem functioning (**Figure 1**).

Nevertheless, the biodiversity-mediated effects of environmental change on functioning may depend largely on the kinds of species that survive in the face of each change driver. The contribution of each species to ecosystem functioning, as well as the potential for complementary niche partitioning, will ultimately depend on the traits of each species present in the community. Accordingly, functional traits, and more specifically functional-trait composition and diversity within assemblages, are now widely recognized to drive ecosystem processes and services (Diaz and Cabido 2001; Lavorel and Garnier 2002; Hudson et al. 2011). In fact, it has even been suggested that functional traits should be the key unit of scientific inquiry for community assembly processes—especially in regard to environmental change (McGill et al. 2006). Therefore, knowledge of the ways in which changes in the environment may impact functional trait composition, diversity, and associated functional assembly processes is of vital importance not only to ecologists but to the human society as a whole (Chapin et al. 1996; Costanza et al. 1998; Balmford et al. 2002).

4.19.4 Functional Response Traits and Functional Assembly within Communities

A basic tenet of community assembly theory is that 'filters,' both abiotic and biotic, select species from the regional species pool to assemble a local community most suited to the prevailing conditions, in a process known as ecological sorting (Weiher and Keddy 1995; Diaz et al. 1998; Ackerly 2003). These filters then continue to act on the community, thereby altering its composition as the parameters of the filters themselves change (Diaz et al. 1998; Shachak and Boeken 2010).

Traditionally, community assembly via environmental filters has been viewed at the species level, where species are individually sorted from the regional pool (Shipley et al. 2006). However, more recently, it has been recognized that species can be grouped according to their functional trait associations, where species within each group share a number of nonrandomly associated functional traits (Diaz et al. 1998; Ackerly 2003; Fynn et al. 2011). When these traits are used to measure the community response to environmental change, any species sharing such traits can be grouped into 'functional response types' (Lavorel and Garnier 2002; Suding et al. 2008). It is these functional traits that may be acted upon by community assembly processes (Lavorel and Garnier 2002; Fukami et al. 2005; Holdaway and Sparrow 2006; Webb et al. 2010), with environmental filters determining the optimal trait values, abundances, and composition at any one site (Messier et al. 2010; Fynn et al. 2011).

If this model is accurate, and community assembly for trait-based functional groups is deterministic (e.g., controlled by environmental filters (Fukami et al. 2005)), then the impacts of environmental change on the functional traits of assemblages will be unavoidable. Assembly still technically occurs at the species level; however, species with similar suites of traits respond to selection pressures in a similar way—resulting in selection by change drivers for functional response groups as a whole (Lavorel and Garnier 2002; Webb et al. 2010). The widely recorded link between species traits and environmental conditions bears testament to this fact (Diaz et al. 1998; Ackerly 2003; McGill et al. 2006; Laliberté et al. 2010), and there are a growing number of examples of environmental change drivers affecting optimal values of traits that are likely to carry implications for ecosystem functioning.

4.19.5 Environmental Changes Select for Functionally Important Traits: Examples

Suding et al. (2008) proposed that, as a result of environmental change, directional changes in biotic and abiotic controls of ecosystems would occur, translating into subsequent directional changes in trait distributions and composition within plant communities. Already well documented are the general patterns of changes in response traits that we might expect to see in regard to specific drivers. However, what is not well documented is the subsequent implications of such response patterns for ecosystem functioning—both in terms of magnitude and persistence. In the following examples, we present instances of single environmental change drivers selecting for specific values of potentially functionally important traits, with their probable effect on ecosystem processes.

4.19.5.1 Plant Height Affected by Climate and Land-Use Change

Plant height is generally associated with growth strategy type, with tall, fast growing, light competitive species being at the 'acquisition' end of the acquisition–conservation trade-off—and thus being more palatable (and therefore susceptible) to grazing herbivores. As a result, plant height may be a good indicator of ecosystem biomass turnover, as more palatable species will experience higher turnover rates.

Many functional traits are found to be affected by changes in temperature (Gratani et al. 2000; Pakeman et al. 2008a; Hudson et al. 2011; Yang et al. 2011), and it could be expected that, because arctic and alpine areas are particularly sensitive to temperature increases (Wookey et al. 2009; Yang et al. 2011), selection will be strongest on traits in these regions. Accordingly, an increase in average plant height was found for four tundra species subjected to experimental warming treatments, although there was significant variation within species plots (Hudson et al. 2011). An important point of interest was that these changes were not transitory; plant trait responses were sustained for almost two decades, contrasting starkly with the authors' hypothesis that long-term sustained responses would require a simultaneous increase in nutrient levels. The findings of Hudson et al. (2011) are consistent with the overall general expectation that warming would on average increase plant height (Wookey et al. 2009) and hence affect both biomass turnover rates and nutrient cycling.

In addition to climate effects, the proportion of land transformed across the globe since 1945 is thought to range from between 40 and 50% (Vandewalle et al. 2010). In a study looking at the impact of land-use change on plant functional responses across Europe, the overall trend across the 11 study sites was to see a decrease in plant height with increased land disturbance (Garnier et al. 2007). Interestingly, regardless of the type of land disturbance to which communities were subjected (e.g., grazing, plowing, etc.), there were general commonalities in responses of traits—suggesting that disturbance intensity, not type, was the most important determinant of land-use change effects (Garnier et al. 2007).

The same pattern of association between plant height and intensity of habitat modification was also demonstrated by Diaz et al. (2007), where shorter plants were selected in more intensely grazed areas. The authors looked at grazed systems across a variety of climates, and in general this same pattern was repeated, suggesting that these effects may be widespread. However, Diaz et al. (2007) found no uniform relationships between categories of species such as forbs, graminoids, and woody vegetation, further lending support to the utility of functional-trait classifications, rather than a priori functional grouping of species.

4.19.5.2 Leaf Traits Respond to Climate

Leaf dry mass per unit area (LMA) is a measure of thickness and/or density of leaf tissue, which allows an approximation of leaf dry matter investment per unit of light intercepting area of leaf deployed (Wright et al. 2004). Leaf mass scales up to the ecosystem process of leaf–litter decomposition, with leaves that have a higher LMA (and hence, more dry matter per leaf), decomposing more slowly (Garnier et al. 2007). A decrease in LMA was found with artificial warming for an alpine plant species *Kobresia pygmaea* (Yang et al. 2011) and for a variety of plant species at 11 sites across Europe (Garnier et al. 2007). The fact that identical relationships between LMA and temperature were found over such a diverse environmental range clearly points to this relationship being a generality—with the expectation being that increased warming should accelerate rates of decomposition. This will have significant implications for biomass turnover and nutrient cycling.

Net leaf photosynthetic assimilation rate per unit mass at saturating light levels (Amass) is a response trait that can be used to approximate net primary production (NPP) at the ecosystem level (Wright et al. 2004), and as such, provides a valuable response-effect linkage. A positive relationship between photosynthetic capacity and temperature seems to be a general relationship across very different environments, with increased photosynthetic capacity of leaves being observed in warmer areas of the Mediterranean for the plant species *Quercus ilex*, and for experimentally warmed plots of the tundra species *K. pygmaea* (Gratani et al. 2000; Yang et al. 2011). An extension of these results would suggest that there may be an increase in NPP globally in those regions where warming occurs.

Changes in leaf nitrogen and phosphorus are good approximations of the nutrient acquisition–conservation trade-off, with reduced concentrations of these chemicals relating to a slower and more conservative growth strategy. Leaf carbon concentration was found to decrease with warming for two tundra plant species (though again results were site specific) (Hudson et al. 2011). Similar effects of warming on leaf chemistry were found for *K. pygmaea*, with decreases in leaf carbon, nitrogen, and phosphorus concentrations and a reduction in leaf C:N ratio, which is thought to be due to increased efficiency of N use (Yang et al. 2011). Therefore, warming is seen to favor conservative (N efficient) growth forms. However, this could also be related to increased temperatures driving accelerated growth, and thus nutrient levels in the soil may become depleted, with plants having no choice but to adopt more conservative strategies.

In addition to the above changes in leaf characteristics within species, there can also be changes in community-wide mean trait values. In particular, warmer temperatures can facilitate plant invasions (including by noxious weeds), and invaders may have a different set of traits to the native species in the invaded community (Sandel and Dangremond 2012). For example, a study in California found that exotic species were taller, with longer and wider leaves and higher specific leaf area and leaf nitrogen content than their native counterparts (Sandel and Dangremond 2012). These traits tended to be favored by warmer temperatures, and it was found that warmer areas had higher proportions of exotic species.

4.19.5.3 Body Size Distribution Altered by Land-Use Intensity

Body size of animals is correlated with a large number of life–history parameters, such as metabolic and reproductive rate, dispersal ability, longevity, etc. (Gaston and Blackburn 1995; Cohen et al. 2003; De Roos et al. 2003; Woodward et al. 2005; Reuman et al. 2009). As such, body size has been shown to be an important parameter in the structuring of food webs (Woodward et al. 2005; Otto et al. 2007; Laliberté and Tylianakis 2010) and in the contribution of a species to ecosystem functioning (Larsen et al. 2005; Hoehn et al. 2008). Thus, like the plant traits above, it can be viewed as both a response and an effect trait (see below).

Land-use intensification at local and landscape scales has been shown to select for smaller-bodied species. For example, land-use intensification can reduce the mean body size of bees and wasps (Hoehn et al. 2008; Laliberté and Tylianakis 2010), and larger-bodied bees and dung beetles have also been shown to go locally extinct more rapidly with a loss of natural habitat from the landscape (Larsen et al. 2005). This nonrandom loss of larger-bodied animals has important functional consequences, as body size can be positively correlated with the ability to perform functions such as dung burial and pollination (Larsen et al. 2005; Hoehn et al. 2008).

4.19.5.4 Loss of Functional Groups

The results presented above clearly show that environmental changes can change the parameters of environmental filters, and subsequently change the trait value optima for a number of traits. Shifts in trait optima are also altering community composition, and this presents a new and even more concerning possibility—that, rather than shifts in the magnitude of ecosystem functioning (via selection for new optimal trait values), we may see elimination of entire functional groups, whose spectrum of trait values do not fall inside the newly defined selection criteria of the changed environmental filters (Vinebrooke et al. 2004). In other words, entire functional groups are lost if environmental conditions exceed their tolerance (Hampe and Petit 2005). Such elimination of functional groups could have drastic effects on ecosystem functioning, as single functional groups may drive ecosystem processes (e.g., legumes fixing nitrogen).

The studies by Hoehn et al. (2008) and Larsen et al. (2005), discussed above, showed that land use can drive the loss of pollinator functional effect groups, and that this reduction can significantly impact pollination success. Similarly, climate can drive the local elimination of functional groups. For example, shading due to increased plant height in the Arctic is eliminating lichens and mosses, either completely or reducing them to abundances whereupon they become functionally extinct (Wookey et al. 2009). If the response traits of a species were completely independent of its effect traits, predicting the impacts of environmental changes on ecosystem functioning would be considerably more difficult. However, the above examples demonstrate that the traits of a species may determine both how it responds to environmental change and how it contributes to ecosystem functioning.

4.19.6 Linking Response with Effect Traits

Species can be classified into functional groups within two broad categories: (1) functional response types—a group of species that responds to the abiotic and biotic environment in a similar way; or (2) functional effect types—a group of species that similarly affect ecosystem processes and drive positive effects of diversity on functioning (Diaz and Cabido 2001; Lavorel and Garnier 2002; Suding et al. 2008; Laliberté et al. 2010). Lavorel and Garnier (2002) recognized the need to identify linkages between response and effect traits, and subsequently proposed a framework with which to do so. The main conclusion of their proposed framework was that traits involved in fundamental trade-offs (such as in nutrient acquisition and conservation) would scale up to biogeochemical cycling at the ecosystem level. Such traits could then be used to predict impacts on ecosystem processes, for example those traits that act as both response and effect traits (Garnier et al. 2007; Minden and Kleyer 2011). This idea was further developed by Suding et al. (2008), with the plant trade-offs in question being based on the leaf economics spectrum (Wright et al. 2004; Shipley et al. 2006).

In essence, due to the mechanism of ecological sorting (Ackerly 2003), it could be hypothesized that functional reassembly will occur in all communities subject to the effects of global environmental change (Shachak and Boeken 2010). Such changes in functional composition and diversity present a worrying unknown, as rates and magnitudes of ecosystem processes are consistently found to be closely associated with these two measures (Diaz and Cabido 2001).

Therefore, linking the responses of such assemblages, both in their initial assembly and reassembly of already established communities, to the effects of environmental changes on ecosystem function has become a paramount issue for the earth science community. Most importantly though, the response–effect trait framework provides a powerful way to determine how the ecological and evolutionary selection pressures of multiple change drivers (and their effects on biotic and abiotic filters) could impact ecosystem functioning (Diaz et al. 1998; Shachak and Boeken 2010). That is, individual drivers of environmental change may select for novel trait distributions within a functional group (Webb et al. 2010) or select certain functional groups nonrandomly over others, thereby altering functional composition and potentially eliminating (or adding) entire functional groups (Diaz and Cabido 2001; Vinebrooke et al. 2004). The combined effect of multiple drivers, and whether their effects will be additive, synergistic or antagonistic, will thus be determined by the extent to which their selective effects on species traits are positively or negatively correlated.

4.19.7 Response Diversity and the Possibility of Co-Tolerance

Response diversity refers to the number of different functional response types represented within one functional effect type—that is, how functionally similar species differentially respond to the same environmental changes (Elmqvist et al. 2003; Laliberté et al. 2010). In light of the previous discussion, this 'response diversity' will play a critical role in determining the continued maintenance of ecosystem functioning in changing environments. This is because functional effect types with high response diversity are more likely to have at least one response type that falls within the trait optima of the new selection regime.

For many plant species, extended growing seasons translate into selection for plant traits that allow an increase in productivity (Piao et al. 2007), especially for high-latitude species (Keyser et al. 2000). However, a recent study manipulating growing season length of three alpine species (by controlling timing of snow melt) found no such effects. The lack of response was attributed to the fact that all three species were 'periodic' species and thus genetically constrained in terms of their growth period (Baptist et al. 2010). This highlights an important aspect of response diversity (and in this case the lack thereof). All three plant species contributed to NPP (which can be approximated by above-ground biomass) but show the same 'fixed' response to climate; they are unable to increase ecosystem productivity even when environmental conditions will allow such an increase. Thus, low response diversity can be an important limiting factor in ecosystem functioning.

It therefore becomes important to know whether specific environmental changes cause a reduction in response diversity, as this will affect resilience to further perturbations. The above examples of drivers selecting for certain trait optima suggest that extinctions will in general not be random (e.g., Larsen et al. 2005). Rather, species with similar traits will be lost (see 'Loss of functional groups' section above), and this could be expected to drive a loss of response diversity when whole response types go extinct. To test this hypothesis, Laliberte et al. (2010) conducted a meta-analysis of 18 data sets of land-use intensification studies, and found that 9 of the data sets displayed a negative relationship between land-use intensity and response diversity. This statistically significant result demonstrated that response diversity is depleted as a result of increasing intensification land-use practices. Moreover, a loss of response diversity driven by one change driver (e.g., land use) could reduce the ability of a system to cope with other additional drivers (Elmqvist et al. 2003). The extent to which this occurs will depend ultimately on whether or not the optima selected by different drivers are correlated. In other words, do both drivers select for the same response traits, such that one driver generates communities that are able to withstand another driver, or do the drivers pull the response traits of a community in different directions (**Figure 2**)?

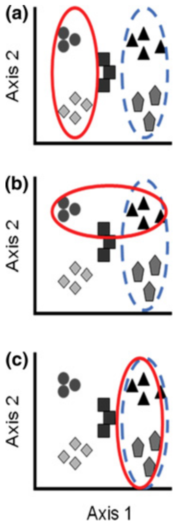

Figure 2 Ordination plots of hypothetical multivariate response traits under the effect of two environmental drivers. Points (species) that are close together have similar combinations of (correlated) traits, and those that are most similar form a functional group (those points with the same shape). Two drivers (dashed and solid ovals) each select for certain functional traits, with those species outside of the selection area being driven locally extinct. Depending on the degree of correlation in the traits selected by each driver, they may exhibit (a) no co-tolerance, (b) partial co-tolerance, or (c) complete co-tolerance.

Vinebrooke et al. (2004) suggested that the sensitivity of a species to different stressors could be positively or negatively correlated. When generalized across a community, a positive correlation would result in species persisting that are more tolerant of subsequent environmental stressors, following elimination of a subset of vulnerable species by the initial stressor. Conversely, negative correlation would result in more susceptible species being left to be acted upon by subsequent stressors. If such co-tolerance occurs among functional groups in the same way as species, then the direction of co-tolerance will determine the extent of functional-diversity loss under a suite of environmental changes (Figure 2). Specifically, we would expect to see less of a decrease in response diversity where there was positive co-tolerance, and an accelerated reduction in response diversity where there is negative co-tolerance.

Co-tolerance of species and functional groups to environmental changes thus provides a framework for understanding how multiple drivers may alter ecosystem functioning. Indeed, to fully understand the cumulative effects of environmental change on ecosystem functioning, we must better understand the potential non-additive effects on ecosystems of multiple change drivers acting simultaneously.

4.19.8 Evidence of Interactions among Drivers

Above, we have outlined how environmental change drivers may select for optimal values of key functional traits. Although in some cases two different drivers may select for the same trait optimum (functional trait co-tolerance), any divergence in optima could produce non-additive effects on ecosystem functioning. The idea that multiple drivers of change may have non-additive effects on species and ecosystems is gaining momentum in the literature, though many studies still focus on only one driver, and where multiple drivers are addressed, interaction effects are often not considered (Vinebrooke et al. 2004; Didham et al. 2007; Tylianakis et al. 2008a). The independence of different drivers is often assumed implicitly, when the effects of one driver are presented without reporting the context of any other drivers. Nevertheless, numerous studies have uncovered interactive effects of multiple drivers on endangered species (Didham et al. 2007), biodiversity (Brook et al. 2008), and species interactions (Tylianakis et al. 2008a). In fact, even a meta-analysis that attempted to argue for the rarity of synergistic effects (among broadly defined ‘stressors’) revealed that 77% of studies showed non-additivity in the effects of multiple stressors, of which 35% were synergies (effects greater than the sum of each stressor in isolation) and the remainder were antagonistic (sub-additive) effects (Darling and Cote 2008).

Didham et al. (2007) described two pathways through which environmental change drivers may have interactive effects on species. The first of these was termed an ‘interaction chain effect,’ whereby one driver affected the extent or level of another driver, but the per unit effect of each driver remained constant. For example, elevated CO_2 (one driver) drives an increase of night-time minimum temperatures (Steeneveld et al. 2011, (another driver)), though CO_2 does not necessarily alter the per unit (e.g., per degree of change) effect of warming. In contrast, the second pathway, which was called an ‘interaction modification effect’ (Didham et al. 2007), requires one driver to affect the per unit effect of another driver. For example, nutrient addition (e.g., through land-use change or N deposition) can promote lower root:shoot ratios in grassland plants, making them more susceptible to a given level of drought (Givnish 1994).

Although these concepts were applied to species, analogous processes could occur in the selection of functionally-important traits. Interaction chain effects could operate in a similar way, and modification effects could occur through context dependency in the effect of drivers on trait optima (Pakeman et al. 2008b). For example, the earlier example of warming selecting for taller tundra plant species could easily be exacerbated by nitrogen or phosphorous deposition reducing nutrient limitation of taller species. The earlier examples of context dependency in the biodiversity-ecosystem functioning relationship provide another possibility for interaction modification effects. In this case, the per unit indirect (biodiversity-mediated) effect of one driver would depend on the extent of another driver (e.g., trait diversity becomes more important for productivity under nutrient enrichment, Laliberté and Tylianakis 2012).

Relatively few studies have examined the effects of multiple drivers on biodiversity and/or ecosystem functioning, compared with the number of studies measuring effects of single drivers, or of multiple drivers affecting, for example, the physiology of a single species. However, a lack of information about interactions was cited by the Millennium Ecosystem Assessment (2005, p. 101) as a major limitation to scenarios for the future of ecosystem services. Furthermore, when Sala et al. (2000) explicitly addressed interactions among drivers, they found that the inclusion of interaction effects severely altered biodiversity outcomes. Given the myriad potential interaction chain and modification effects among all of the drivers of environmental change, and the likelihood of negative co-tolerance as drivers select for different trait optima and exert differential effects on species physiology, we expect that an increasing number of studies will demonstrate non-additivity in the effects of multiple change drivers on biodiversity and ecosystem functioning.

For example, a recent review by Schweiger et al. (2010) concluded that changes in local and regional climate and invasive species would generate novel communities, with potential effects on ecosystem functioning. Generalist species are likely to be favored by both of these drivers, invaders may preferentially interact with other invaders to the exclusion of native species (Aizen et al. 2008), and changing climatic conditions might promote further invasions (an interaction chain effect sensu Didham et al. 2007; Schweiger et al. 2010). Thus, the interactive effect of these drivers may alter biodiversity and select for traits such as generality.

Selection of functional traits may be a key mechanism through which environmental change drivers may interact; however, any of the pathways through which changes can affect ecosystem functioning (Figure 1) are potentially subject to non-additivity when multiple drivers occur in combination. Yet, despite the known importance of this non-additivity for extinction of species, disruption of interactions, and the future of biodiversity (Sala et al. 2000; Didham et al. 2007; Brook et al. 2008; Tylianakis et al. 2008a; Schweiger et al. 2010), most national and international policy mechanisms are aimed at mitigating a single driver of environmental change (e.g., the Kyoto protocol, agri-environment schemes, and at least 16 international legal instruments have programs or activities that are relevant to invasive species). Although the reasons for this disconnect are likely to be pragmatic, rather than philosophical, mitigation of the cumulative risks to ecosystem functioning will ultimately require communication and coordinated action among these policy mechanisms.

4.19.9 Conclusions and Implications

The Earth's ecosystems are at the verge of passing into what is described by Suding et al. (2008), as 'no-analogue' functional communities. Anthropogenic drivers of environmental change are an ecological pressure unique to our time. The uniqueness of these drivers translates into unique changes in functional trait composition, diversity and abundance; as these drivers act as ecological filters and cause functional reassembly of communities. If we are ever to predict such changes, traits with both response and effect linkages must be further identified and more widely used in studies looking at ecosystem responses to environmental change. The generalized frameworks of Lavorel and Garnier (2002) and Suding et al. (2008) will make this undertaking much more accessible.

Finally, the impacts of multiple drivers on communities, particularly interaction effects, need to be more widely recognized, reported, and incorporated into policy. While assessing interactions between drivers may be viewed as requiring more involved and complicated experimental designs, this may not be the case—many published studies already have the relevant data, and even reporting explicitly the environmental context of experiments could provide useful information. In terms of mitigating effects of environmental change, our greatest challenge will be to understand how changes to biodiversity, community structure, and trait optima brought about by one driver may provide greater or lesser resilience against another. In essence, the responses of biotic communities to a suite of environmental change drivers, and their link to myriad ecosystem services, will ultimately determine our survival.

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4.20 Desertification of Rangelands

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Glossary

Alternative states Ecosystems with similar climate and soils, yet different species, interactions, and processes.

American Southwest The arid region (<25 cm rainfall per year) of the United States that includes the three hot deserts (Chihuahuan, Sonoran, Mojave).

Desertification The broad-scale shift from productive, native perennial grasslands or savannas to dominance by native or non-native annuals, unpalatable herbaceous and woody plants, and/or increasing amounts of bare ground.

Grassland Ecosystem where the vegetation is dominated by grasses and other herbaceous (nonwoody) plants, such as forbs.

Invasive species native or non-native species that have increased dramatically in an ecosystem as a result of changes in climate and/or human activities.

Novel ecosystem Ecosystem comprised of different species, interactions, and processes not possible under current conditions and not reflected in past systems.

Savanna Ecosystem characterized by a mixture of grasses and woody plants (shrubs, trees) where the woody plants are sufficiently small or widely spaced so that the canopy is not closed. The open canopy allows sufficient light to reach the ground to support the herbaceous layer of grasses.

Shrubland Ecosystem dominated by short (typically <8 m tall) woody plants often with many stems.

Soil inorganic carbon (carbonate) Compounds in the soil containing carbon that are not created by living organisms, but are derived from minerals in the Earth. The most common form of carbonate in dryland soils is calcium carbonate ($CaCO_3$) that forms when minerals are leached by rainwater from upper layers of the soil and accumulate in lower layers. Hardened deposits of calcium carbonate are called caliche.

Soil organic carbon Compounds in the soil containing carbon material derived from decaying vegetation, bacterial growth, and metabolic activities of living organisms or chemicals.

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4.20.1 Introduction

Arid and semi-arid grasslands and shrublands (i.e., dryland ecosystems) comprise nearly 40% of the Earth's land surface and influence the livelihood and well-being of one-fifth of the world's human population (Reynolds and Stafford Smith 2002). Plants and animals associated with these ecosystems often exist near their physiological limits such that slight increases in temperature, decreases in precipitation amount, or shifts in seasonality can have disproportionately large effects relative to those in other ecosystems. Furthermore, changes in the abundance and cover of vegetation in these drylands can have profound effects on soil erosion and exchanges of energy and water between the land surface and the atmosphere; these bottom-up effects can intensify stresses associated with climate and act to initiate self-reinforcing changes in vegetation (feedbacks). As a result, arid and semi-arid grasslands are highly susceptible to desertification – the broad-scale shift from productive, native perennial grasslands or savannas to dominance by native or non-native annuals, unpalatable herbaceous and woody plants, and/or increasing amounts of bare ground. As reviewed in this chapter, these ecosystem modifications have significant consequences for myriad ecosystem provisioning, regulating, supporting, and cultural services via their influence on carbon storage, biodiversity and forage production, spread of invasive non-native species, the partitioning of hydrological budgets, wind and water erosion, and land surface influences on atmospheric chemistry and weather. The social aspects of the vulnerability of these ecological systems to change are discussed in Ojima et al. (in press, see Chapter 4.17).

Desertification is the result of cumulative threats that interact in time and space (Figure 1). Each threat operates on ecosystems at local scales that can propagate to influence broad-scale dynamics with consequences for ecosystem services. Carbon dioxide enrichment (CO_2), nitrogen (N) deposition, and climate are broad-scale; regional threats that constrain or amplify effects of finer-scale threats and responses to weather events (Figure 2). These local threats include the following:

1. Extreme weather events (drought, flood, wind storms)
2. Land use (human preemption of landscapes, including suburbanization, dryland farming and fragmentation)
3. Land management (primarily livestock grazing, noxious plant management)
4. Establishment and spread of non-native species

Both the broad-scale drivers and local threats are changing through time such that the future of drylands is highly uncertain. For example, surface air temperatures are increasing in some regions for at least part of the season, and atmospheric CO_2 levels are increasing globally, yet global climate models disagree on how precipitation will change in magnitude, seasonality, and even direction (increase, decrease) in drylands. Nitrogen deposition may increase or decrease in the future depending on the source of nitrogen inputs into the atmosphere and the geographic location (e.g., proximity to cities). Local threats are also changing, and in many cases these changes are nonlinear through time and space, and depend on interactions among broad-scale drivers, land surface and ecological characteristics, policy decisions, and local management practices.

In the future, interactions among broad-scale drivers and localized threats are expected to increase the likelihood of creating alternative ecosystem states (e.g., grass states shrub states; perennial plant states annual plant states, etc.). When coupled with changes in atmospheric chemistry, such as CO_2 concentrations and N-loading, these threats are likely to create 'novel ecosystems' (ecosystems comprised of different species, interactions, and processes not possible under current conditions and not reflected in past systems). These alternate states will have different consequences for ecosystem services. Our challenge in this chapter is to determine the vulnerability of different ecosystem services to changes in drivers and ecosystem states, with a focus on the American Southwest. In addressing this challenge, we first sought to (1) briefly describe key ecosystem services in drylands, (2) identify and articulate the consequences of desertification to each ecosystem service (historical to current-day perspective), and (3) explore the vulnerability of each ecosystem service to future state-change effects if existing threats intensify and new threats emerge. We then synthesize this information to determine the threats expected to have the greatest future impact (positive–negative) on desertification and ecosystem services for alternative states, and provide potential actions for mitigation. We conclude with recommendations for land managers, policy makers, and other stakeholders.

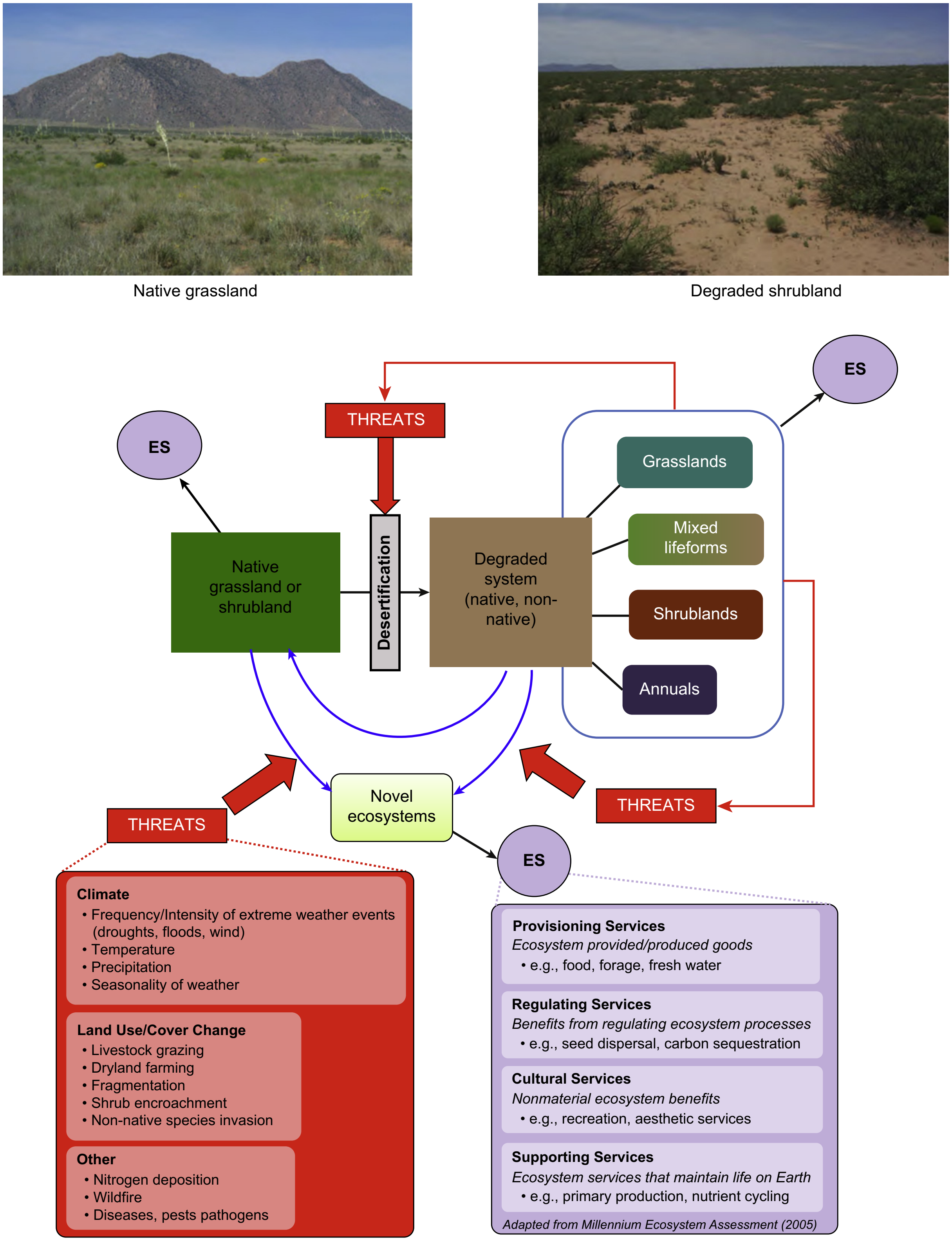
4.20.2 Effects of Desertification on Ecosystem Services

4.20.2.1 Regulating Services

4.20.2.1.1 Energy Exchange and Land–Atmosphere Interactions

Understanding how various drivers of environmental change interact to affect the Earth's energy balance is one key to understanding the future state of the Earth system and how humans will need to adapt in order to live more sustainable. Energy balance is the difference between the total incoming and total outgoing energy within the Earth's atmosphere, because the Earth receives almost all of its radiation from the sun – an energy balance of 0 means that all incoming radiation from the sun equals all outgoing radiation. If energy balance increases above 0, the Earth's atmosphere will warm, and it will cool if the energy balance falls below 0. This balance is closely met on the annual average, but intraannual values are not. Many factors control how much energy from the sun arrives at the Earth's surface each year (e.g., sun spots, orbital patterns of the Earth, clouds), how the radiation reaching the surface is reflected or absorbed (e.g., soil color, snow cover, vegetation type and density, soil moisture content), and the extent to which it is trapped or re-emitted back into space by greenhouse gases. The influence of these factors (known as radiative forcing potential) can be assessed for their respective capacity to alter energy balance (Baldochi, in press see Chapter 4.10).

Properties and processes controlling radiative forcing potential in dryland ecosystems have received increased scientific attention for at least three reasons: (1) Arid landscapes with low vegetative cover and high bare ground cover are typically a net sink for radiation and a net source of heat energy to the atmosphere; (2) the land surface area covered by arid landscapes



Native grassland

Degraded shrubland

ES
THREATS
ES
Grasslands
Mixed lifeforms
Shrublands
Annuals
Native grassland or shrubland
Desertification
Degraded system (native, non-native)
Novel ecosystems
THREATS
THREATS
ES
Climate
• Frequency/Intensity of extreme weather events (droughts, floods, wind)
• Temperature
• Precipitation
• Seasonality of weather
Land Use/Cover Change
• Livestock grazing
• Dryland farming
• Fragmentation
• Shrub encroachment
• Non-native species invasion
Other
• Nitrogen deposition
• Wildfire
• Diseases, pests pathogens
Provisioning Services
Ecosystem provided/produced goods
• e.g., food, forage, fresh water
Regulating Services
Benefits from regulating ecosystem processes
• e.g., seed dispersal, carbon sequestration
Cultural Services
Nonmaterial ecosystem benefits
• e.g., recreation, aesthetic services
Supporting Services
Ecosystem services that maintain life on Earth
• e.g., primary production, nutrient cycling
Adapted from Millennium Ecosystem Assessment (2005)

Figure 1 Historically, the predominant state change in arid and semi-arid regions globally was associated with desertification, the broad-scale conversion of perennial grasslands, shrub-steppe, and savannas to systems dominated by xerophytic, unpalatable shrubs on degraded soils or to annuals on degraded soils. Desertification results from cumulative, interacting threats that may intensify with regional climatology. Degraded systems, in turn, would be vulnerable to future threats that may lead to alternative states, including novel ecosystems. Future threats would also influence the rate and extent to which management can repair or restore degraded systems to prior and more desirable states. As state changes occur, ecosystem services (ES) would be impacted. (Photos from Jornada USDA-LTER photo library.)

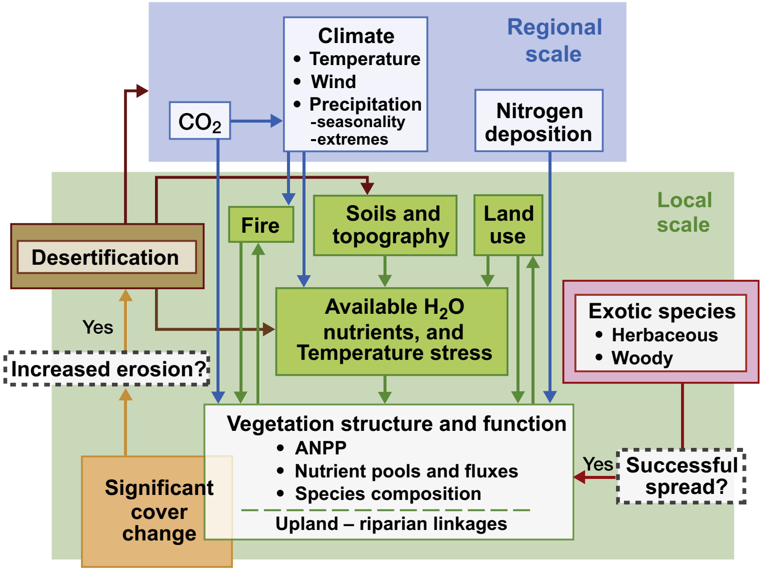


Figure 2 Organizational framework for interpreting climate, land cover effects, and their feedbacks on desertification of dryland ecosystems at local and regional scales (Ryan et al. 2008).

is increasing globally with desertification (Archer 2010); and (3) ecosystem states accompanying desertification (Figure 1) positively reinforce and sustain altered microclimatic conditions of desertified states, thereby making it difficult to restore former ecological states such as grasslands. Additionally, many arid regions such as the American Southwest could become drier and experience more extreme climatic events, such as prolonged droughts and flooding events (Seager et al. 2007). Impacts of increasing human populations, altered land use, and introduced species are expected to interact with climate to influence land–atmosphere interactions with feedbacks to climate and sustainability of drylands in the future. Understanding the sustained and cumulative impacts, and potential tipping points associated with such change remains an urgent challenge to researchers, policy makers, and land managers.

Consequences of Desertification for Energy Exchange and Land–Atmosphere Interactions

Transitions between grasslands and shrublands can alter the energy balance of arid landscapes over relatively large areas (Figure 3; Beltran-Przekurat et al. 2008; Nair et al. 2007). Due to the typically lower vegetation cover and greater reflectivity of soil compared to plants, sparsely vegetated shrublands reflect a larger amount of incoming radiation than grasslands with a lower albedo (Kurc and Small, 2004). When water is lost from soils (evaporation) and plants (transpiration), cooling can occur because energy is dissipated as water transitions from a liquid to a gaseous state (latent heat exchange). This loss of energy to the atmosphere depends on a number of factors, including soil physical properties and moisture content, leaf area within the plant canopy, and the capacity of air masses within the canopy to mix with air above it. The latter is controlled by factors such as wind speed, roughness, and vertical structure of the plant canopy.

Many differences in the partitioning of surface energy balance between grasslands and shrublands depend on the differences in the biology between grasses and shrubs, such as their physiology and timing of growth (C_4 grasses in summer, C_3 shrubs in spring and fall), their root distributions (shallow-rooted grasses can be more coupled to precipitation compared with deep-rooted shrubs that access stored water), and canopy structure (dense bunchgrasses, open shrub canopies). Thus, impacts of shrub encroachment on energy balance can differ among desert systems (Eldridge et al. 2011), and the dynamics at one site do not necessarily translate to others. The need for a more robust understanding of the consequences of land cover change on ecosystem energy balance is a key motivation for desertification research.

Land cover changes that modify surface energy balance affect a gamut of local to global ecosystem goods and services. On a local scale, the increased heat storage associated with depleted soil moisture and altered land surface properties in shrublands can promote water stress and limit photosynthesis in grasses, thereby reducing their productivity, biomass (see Section 4.20.2.3.1), and forage production (see Section 4.20.2.2.2), while creating conditions conducive to the establishment of unpalatable, xerophytic shrubs. In shrublands, soil moisture is likely to be reduced at greater depths due to the deeper penetration of shrub roots compared to grasses (Gibbens and Lenz 2001). Because of the large expanses of shrublands, these local effects manifest to impact landscape to regional scale processes, including sensible and latent heat exchange, heat storage, and surface water balance. These changes can influence and potentially alter regional climate by depleting atmospheric moisture, decreasing cloud cover, and increasing drought cycles as well as modifying radiative forcing potential.

Threats to Future Trends in Energy Exchange and Land–Atmosphere Interactions

Changes in surface energy balance, accompanying and underpinning future stresses of desertification have the

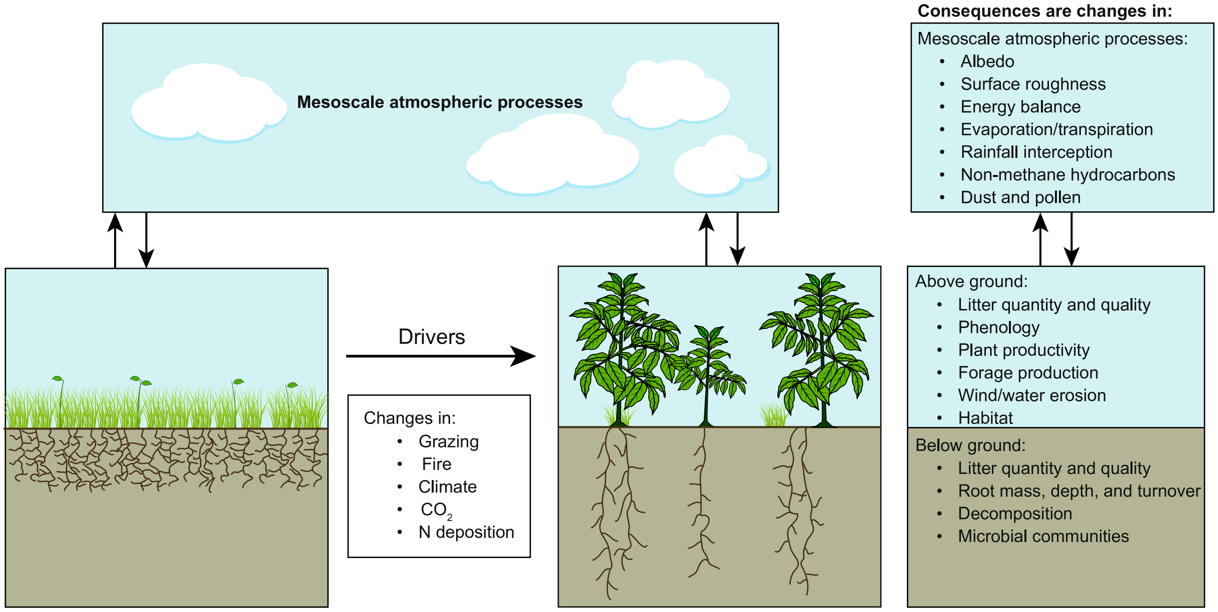

Consequences are changes in:
Mesoscale atmospheric processes
Mesoscale atmospheric processes:
Albedo
Surface roughness
Energy balance
Evaporation/transpiration
Rainfall interception
Non-methane hydrocarbons
Dust and pollen
Drivers
Changes in:
Grazing
Fire
Climate
CO2
N deposition
Above ground:
Litter quantity and quality
Phenology
Plant productivity
Forage production
Wind/water erosion
Habitat
Below ground:
Litter quantity and quality
Root mass, depth, and turnover
Decomposition
Microbial communities

Figure 3 Drivers interact to influence state changes from grass to woody plant dominance with potential consequences for changes in above and below ground ecosystem structure and function, and land surface–atmosphere interactions. Carbon sequestration by plant–soil–microbial processes occurs both above and below ground (Archer 2010).

potential to affect a range of stakeholders over a sustained period of time, due to the broad spatial extent of these changes and the reinforcing feedbacks associated with altered ecosystem states. Warmer, drier conditions accompanying grassland to shrubland conversion would reinforce the displacement of relatively palatable mesophytic grasses by unpalatable xerophytic shrubs with reductions in overall plant productivity, livestock carrying capacity, and vegetation cover (Fredrickson et al. 1998; Barger et al. 2011; Peters et al. 2011). Associated with these changes would be the opportunity for invasion from exotic species, and altered human well-being and health through the increased capacity for dust storms – especially during periods of prolonged drought forecast for the region (see Section 4.20.2.3.2). At a larger scale, reductions in atmospheric uptake potential or enhanced radiative forcing potential of shrublands (see Section 4.20.2.1.2) may result in increased reliance on ecosystems in other bioclimatic zones to uptake carbon dioxide.

4.20.2.1.2 Carbon Storage (Organic, Inorganic)

The amount of carbon released into the atmosphere each year via fossil fuel combustion is estimated at 5.5 Pg (IPCC 2007). While this is a small component of the annual global carbon budget, the cumulative effects on the atmosphere can be quite important. Since 1850, the atmospheric concentration of carbon dioxide (CO_2) has increased from 275 ppm to more than 390 ppm. This increase in atmospheric CO_2 and other greenhouse gases (GHG) is a major contributor to documented increases in average global surface temperature (1 °C since 1900), and is hypothesized to have major impacts on regional climate (Seager et al. 2007). Substantial resources have been devoted to developing GHG mitigation technologies to reduce emissions; however, carbon sequestration in natural and managed ecosystems remains the only economically viable means of removing carbon from the atmosphere (Pacala and Socolow 2004; but see Section 4.20.4). Vegetation, via photosynthesis, takes up carbon in the form of CO_2 from the atmosphere, converts this greenhouse gas into complex organic structures, and then transfers it into the soil with the death and decomposition of plant leaves, roots, and stems. This organic plant debris is then converted to other stable carbon compounds via microbial assisted processes. The regulation of climate via CO_2 sequestration by plant–soil–microbial processes (Figure 3) is an important ecosystem service threatened by desertification where both the levels of stored soil carbon and the capacity to increase its storage are diminished. In addition, many drylands are heavily grazed and the carbon removed by grazers is exported off-site. Here we discuss both organic and inorganic soil carbon that are important in arid and semi-arid regions of the world, including the American Southwest.

The amount of organic (readily exchangeable) carbon stored in soils and vegetation globally exceeds 2000 Pg (1 Petagram = 10^{15} g = MMT). Soils contain 1400–1600 Pg of organic carbon, and vegetation is estimated to contain 500–600 Pg (IPCC 2007). Of this total amount, about 120 Pg moves back and forth between the soil–vegetation complex and the atmosphere on an annual basis (flux). By comparison, oceans with the largest pool contain about 38 000 Pg and the atmosphere contains about 750 Pg. Dryland ecosystems contain approximately 363 Pg of carbon (Post et al. 1982). This pool of carbon is equal to the amount stored in croplands and wetlands combined (370 Pg), and is only slightly less than pools associated with forest ecosystems (470 Pg). Although drylands represent a significant portion of the global soil carbon pool, managing them for an increase in storage is a challenge. For any specific unit of land, high spatial variability and year-to-year changes in factors controlling carbon flux (precipitation, temperature) make management highly uncertain, and prediction and measurement difficult and expensive. At larger scales, the same problems are confounded by the vast areas involved, and make credible accounting systems and the policies and programs they support difficult to construct.

Inorganic carbon, stored as calcium carbonate ($CaCO_3$), is also a significant portion of the global carbon budget (**Figure** 4(a)). The global amount exceeds 940 Pg, making it the third largest carbon pool (Eswaran et al., 2000). Inorganic carbon exists in arid and semi-arid soils as light colored subsoil horizons that develop when small calcite crystals (2–10 μm) are precipitated in the pore spaces between sand and silt particles. The longer a dryland soil has been exposed to weathering at the Earth's surface, the greater the amount of inorganic carbon in its subsoil.

The role that inorganic carbon plays in the global carbon cycle, especially with respect to carbon storage, is more complicated than organic carbon because it depends on the

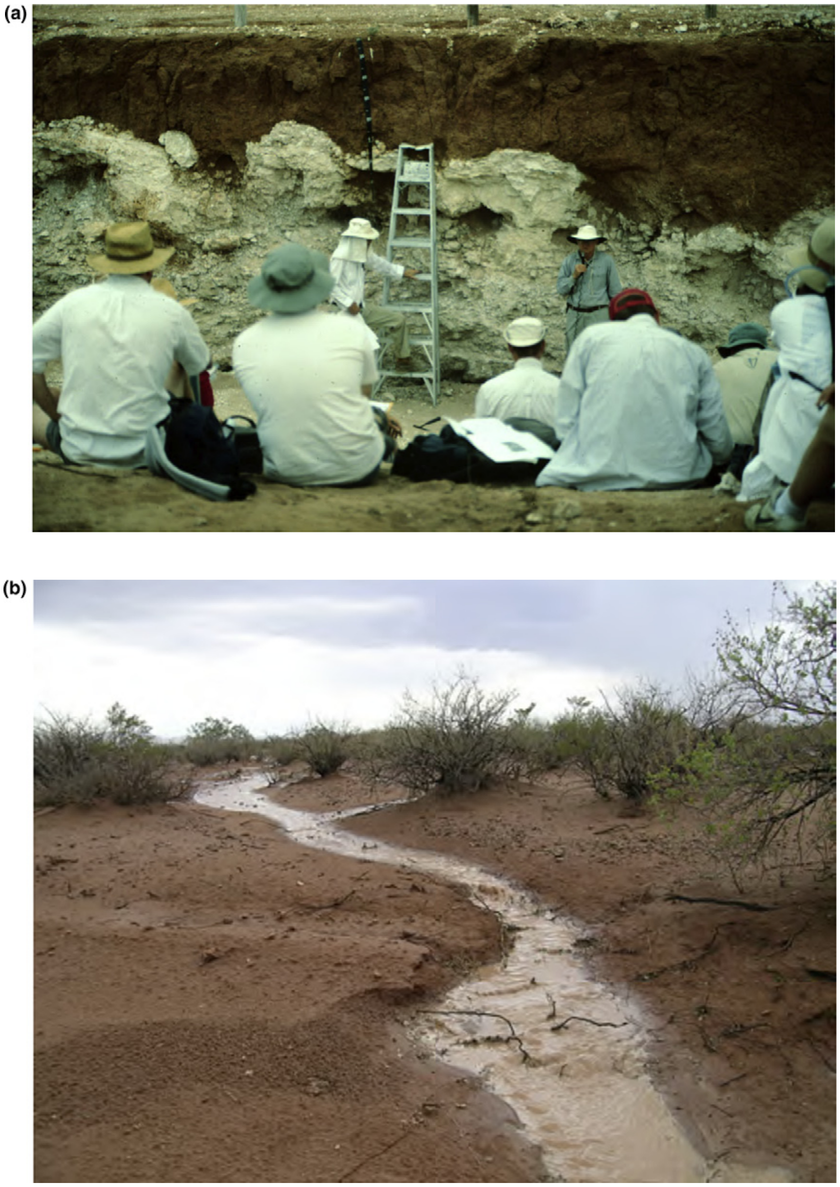


Figure 4 (a) Inorganic carbon (shown as light colored layer at variable depths), stored as calcium carbonate ($CaCO_3$), is a significant portion of the global carbon budget. Lee Gile and John Hawley in background (Photo from Jornada USDA-LTER photo library). (b) High connectivity of bare areas in shrublands compared to grasslands results in higher runoff and greater losses of nutrients and sediments (photo credit: Brandon Bestelmeyer (USDA)). (c) A massive dust storm moves across Phoenix on 5 July 2011. Photo by Dave Seibert/The Arizona Republic (http://www.azcentral.com/photo/Community/PhoenixCentral/19441). (d) Prescribed fire is an important tool used to prevent shrub encroachment into arid and semi-arid perennial grasslands. Photo credit: Guy McPherson (University of Arizona).

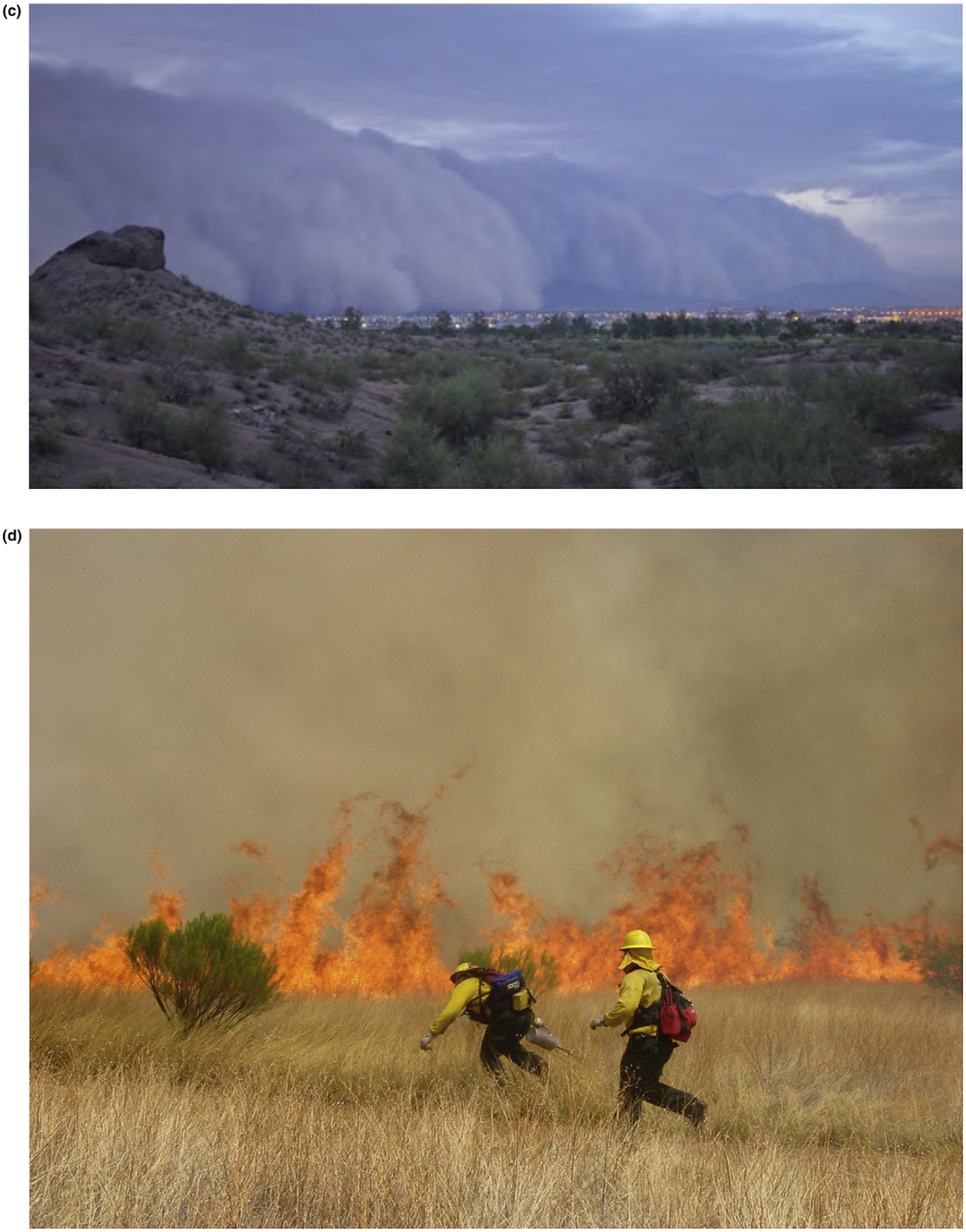


Figure 4 (*Continued*).

calcium biogeochemical cycle. A lexicon to explain how and when different types of inorganic carbon are formed is still developing. For example, 'Soil Carbonate' is the broadest category and refers to the total amount of carbonate in soil. This category is subdivided into 'Lithogenic Carbonate' (carbonate particles physically derived from limestone or similar bedrock) and 'Pedogenic Carbonate' (carbonate crystals precipitated from solutions in the soil). If the source of calcium in pedogenic carbonates is from preexisting carbonate minerals, such as particles of limestone, there is no gain in carbon storage with its formation. This is because the amount of carbon dioxide (CO_2) consumed to form carbonic acid, which reacts with and dissolves the limestone particles, is the same amount of CO_2 released upon the formation of pedogenic carbonate (Monger and Martinez-Rios 2000). However, pedogenic carbonates whose calcium is derived from silicate minerals is a potentially strong sink for atmospheric CO_2 because the carbon in the $CaCO_3$ precipitate is derived from CO_2 respired from roots and microbes; this CO_2 could otherwise leave the soil and return to the atmosphere.

Consequences of Desertification for Carbon Storage

Drylands with low plant production (see Section 4.20.2.3.1) and low organic soil carbon are vulnerable to extreme weather events (e.g., drought) and disturbance, such as livestock overgrazing (**Figure 1**). Desert grasslands in the American Southwest are typically net carbon sinks. With conversion to shrublands, arid lands tend to become net carbon sources (Barger et al. 2011), and adversely affect air quality by increasing dust loading and the concentration of volatile organic carbon compounds (see Section 4.20.2.3.2). Cases where shifts from grass to shrub dominance do not change the total amount of organic carbon in the soil pool have also been documented. In these instances, the spatial distribution of soil organic carbon (SOC) is strongly impacted, with SOC becoming concentrated beneath shrub canopies with very little SOC in bare soil gaps between plants. This shift in the distribution of SOC has important consequences for soil properties that feed back to influence the availability of water and nutrients to plants, animals, and microbes (see Section 4.20.2.2.1) and the nature of land surface–atmosphere interactions (see Section 4.20.2.1.1).

Desertification also poses a threat to inorganic carbon storage, which contains roughly 10 times more carbon than the amount in soil organic matter. When desertification reduces plant production, the amount of CO_2 respired into the soil and the abundance of microorganisms, which are partially responsible for the precipitation of $CaCO_3$, decline (Monger et al. 1991). In addition, desertification causes erosion and exhumes subsoil horizons. When wind and water erosion expose long-buried inorganic carbon to the geochemical environment at the land surface, $CaCO_3$ can break down and contribute CO_2 to the atmosphere (Serna-Perez et al. 2006; Tamir et al. 2011).

Threats to Future Trends in Carbon Storage

The net storage or loss of carbon in an ecosystem is the balance between carbon uptake by plants and carbon released by plant and microbial respiration. Because levels of soil organic matter are inversely related to mean annual temperature in many arid regions, increases in regional temperature would promote losses of soil carbon to the atmosphere, exacerbating increases in atmospheric CO_2. This accelerated carbon liberation might be compounded by declines in levels of carbon sequestration, which would decrease with decreasing rainfall. Grazing by livestock is the predominant land use in drylands. Excessive grazing is detrimental to plant productivity and can further accentuate declines in soil organic matter. Land management can contribute to the mitigation of radiative warming from atmospheric CO_2 by adjusting practices to increase or protect the amount of carbon (C) stored in soils and vegetation. In particular, stocking at sustainable levels to maintain desirable shrub:grass ratios, responding quickly and decisively to drought to avoid degradation, and developing and implementing technologies, such as appropriate plant materials, reseeding methods, and management guidelines to restore degraded areas could increase soil carbon storage at approximately 0.15 Gt year^{-1} over the next 100 years (Thomson et al. 2008). Although this level of potential C sequestration is relatively low per unit of land area compared to other land-use categories, the vast land area in drylands and strong positive correlation between increased sequestration and other desirable benefits makes sequestration worth pursuing. However, by far the most effective strategy, given the potential for desertification-induced losses of soil carbon in rangelands, is to develop tools, policies, and programs to identify arid lands at risk before they are seriously degraded, and to implement management to halt or reverse the degradation.

4.20.2.2 Provisioning Services

4.20.2.2.1 Water Quality and Quantity

An optimum quantity and quality of water are needed to maintain natural and human ecosystems. The way that land, water, and atmospheric resources in drylands are exploited or developed can have serious effects on ecosystem provisioning and regulating services related to water. Landscapes in drylands are organized into watersheds of different sizes, ranging from small headwater or upland basins to larger watersheds that encapsulate the valley floor. As such, watersheds are critical for water provisioning and use in the American Southwest. However, drylands are continually operating under conditions of limited water availability since evapotranspiration demand greatly exceeds low precipitation amounts. As a result, dryland ecosystems have evolved to maximize their efficient use of water, although episodes of drought or flooding can significantly alter the balance between water availability and ecosystem function.

Many landscape characteristics in drylands, including the spatial distributions of plants and animals, are shaped by the availability and distribution of water and the timing of its delivery. As a result, hydrologic conditions can vary substantially over short distances, with common occurrences of ephemeral channels and isolated perennial reaches fed by shallow groundwater or springs. Although these riparian features occupy less than 1% of the entire landscape, they have disproportionately large impacts on ecosystem productivity and biological diversity. Water availability and its influence on the landscape also have a direct impact on atmospheric conditions, which can lead to short- and long-term feedbacks to weather and climate (see Section 4.20.2.1.1).

The natural scarcity of water in drylands, coupled with the ever-increasing demands for water from rapidly expanding human populations, constitutes a major challenge in watershed management. Stakeholders affected by inadequate amounts and quality of water in drylands include ranchers and pastoralists (livestock), farmers (crops), ecologists (natural vegetation), and the public (recreation, wildlife, residents). As suburban or urban land uses proliferate, additional stakeholders include towns and cities (and their residents) who become important users of water, as agricultural or land-use rights are transferred. These stakeholders can also impact water in drylands through effects of grazing, mining, and urbanization activities on the natural landscape. Mining in the Southwestern United States in particular, has reduced water availability and impacted its quality in areas adjacent to and downstream of excavations.

Consequences of Desertification for Water Supplies

Desertification and the encroachment of woody plants into grasslands have direct impacts on the distribution of water and its quality within landscapes (Huxman et al. 2005). Since plant–water relations are bidirectional, a change in the dominant plant functional type can result in a myriad of impacts and feedbacks in the water, carbon, nutrient, and sediment cycles. Above and below ground plant characteristics affect local radiation, rainfall interception, root water uptake, soil moisture redistribution and litter and soil production, among other processes (**Figure 3**). Higher overall evapotranspiration losses occur when shrublands replace grasslands as a result of larger bare areas and greater plant water use efficiency of shrubs compared with grasses (Dugas et al. 1996). A greater demand for water by shrubs decreases overall water availability, with subsequent impacts on soil moisture, runoff generation, groundwater recharge, and transport of dissolved and particulate matter by water. Shrublands on sandy soils located on level topographic positions have been found to use most or all of the water from precipitation, while grasslands allow some deeper recharge. By contrast, the shift from grassland to shrubland on slopes and rocky soils can increase the amount of runoff and rates of water erosion. The connectivity of bare areas is typically greater in shrublands compared to grasslands, resulting in higher runoff and greater losses of nutrients and sediments (**Figure** 4(b)). This, in turn, translates into losses of soil fertility, the dissection of landscapes into rills and gullies, and increased sediment loads to downstream locations. The latter is the major cause of reductions in water quality in drylands. Interactions at the plant-to-patch scale in grasslands and shrublands aggregate to basins and watersheds, thus affecting water, nutrient, and sediment yield in broader areas.

Finally, dust emitted from desert regions, due to human activities and desertification, has the potential to impact mountain snow hydrology (Painter et al. 2010). Dust deposited on snow can significantly impact the amount of solar radiation absorbed by the snow, increase the rate of melt, and the rate at which meltwater is produced and delivered to river systems. These changes have the potential to impact water management and decrease the amount of water in major river systems (e.g., the Colorado River).

Threats to Future Trends in Water Quantity and Quality

Desertification adversely impacts water and sediment yield. Plausible changes in the intensity, duration, and frequency of precipitation events would accentuate these impacts. For example, the balance between grasses and shrubs which affects numerous ecosystem services is influenced by the amount, timing, and seasonality of precipitation and the size of rainfall events (e.g., Good and Caylor 2011). Should they occur, shifts between summer and winter precipitation or changes in the frequency of extreme storm events that deliver precipitation in short, intense pulses would be expected to tip the balance between grasses and shrubs either directly or indirectly via higher surface runoff, accelerated erosion, and changes in soil moisture and groundwater storage and recharge regimes. Higher temperatures would reduce the effectiveness of rainfall by increasing evaporative demands while concomitantly increasing water requirements and levels of physiological stress in plants and animals. This combination of increased runoff, increased soil evaporation, and reductions in plant performance would alter ecosystem rain-use efficiency.

Increases in convective storm intensity would increase the incidence and magnitude of surface runoff events and associated erosion. This, in turns, would lead to reductions in soil depth (critical for water storage) and fertility on upland sites and hence forage production (see Section 4.20.2.2.2) and ecosystem productivity (see Section 4.20.2.3.1). Particulates and nutrients in the sediments carried in these runoff events would be transported in ephemeral channels and eventually end up in playas or streams where water quality and the life span of man-made structures aimed at capturing water (e.g., ponding dikes, stock dams, and reservoirs) could be reduced.

4.20.2.2.2 Food and Fiber

Drylands contribute significantly to annual global food and fiber production owing to their extensive geographic extent on all continents. About 37% of the total annual global value of food and fiber production originates from drylands. One-half of this value is livestock products, primarily from extensive grazing of cattle, sheep, and goats, and one-half of livestock production globally each year is harvested from drylands used as grazing lands. In addition, about 10% of non-livestock food and fiber production (e.g., cereal grains and cotton) are produced from rain-fed systems in drylands. The remaining dryland food production originates from irrigated systems.

Of the two billion people living on drylands, about 800 million are farmers engaged in food and fiber production. Livestock ownership sustains about 675 million rural poor, predominately in the developing countries of the world. Estimates are that one in ten humans is involved in animal husbandry. Livestock are thus important economic assets and sources of income for rural people on all continents, except Antarctica. Although per capita demand for meat products may be at saturation levels within developed countries, demand for meat products is on the rise within developing countries, including China, Korea, and Brazil (Steinfeld et al. 2010). Demands for meat products are projected to increase 2–3% per annum. Globally, meat production is increasingly from intensive, confined systems, but extensive dryland production systems are the source of many of the animals that are ‘finished’ in confined systems and will continue to supply local meat demands and sustain rural economies, irrespective of a country’s economic status. Domesticated ruminants are well suited to both the biophysical and the socioeconomic conditions inherent to drylands.

In the American Southwest, the issue of food and fiber production from drylands has become less relevant over recent decades, despite growing global demands described above. The use of these lands for food and fiber production has diminished significantly from peak livestock numbers in the mid-twentieth century (Fredrickson et al. 1998). At present, it is common for public land allotments to be unused by livestock. These declines are mirrored across North America: cattle, sheep, and goat numbers (expressed as animal units) have declined by over 25% since 1979. In addition, recent rancher surveys reflect other characteristics of an industry in decline, including increased age of primary owners, smaller herd sizes, and growing importance of non-economic rationales for ownership, such as lifestyle and recreational motivations.

Consequences of Desertification for Food and Fiber

Desertification has had less of an impact upon food production than expected based on meat production. Ruminants have wide dietary preferences, and maintain inherent capacities to digest cellulose regardless of the dietary sources of forage. At least 10–20% of drylands globally are degraded through desertification processes, yet animal production has continued to increase. For example, the dramatic increases over the last two decades in goat numbers, averaging nearly 1.2 million additional goats around the world each month, in part reflect adjustments of meat production systems to altered landscapes and altered socioeconomic conditions. Certainly, degraded conditions due to overgrazing have caused significant reductions in capacities of drylands to produce forage with resulting losses in meat production at certain times on all continents, over the past century. However, the widespread impacts of overgrazing upon food production have likely been overestimated. In addition, within local regions where overgrazing has more recently resulted in degraded conditions, policies have often been implemented to constrain, if not outright ban, continued livestock grazing (Estell et al. 2012).

Threats to Future Trends in Food and Fiber

Degradation associated with land conversion and salinization is expected to influence drylands more so than livestock grazing. Farming on lands marginally suited for crops has been, and will likely continue to be, a major source of land degradation. Cereal production will likely need to increase by 0.5 billion tons per year over the next two decades owing to the demands of increasing human populations. In lieu of unit-area production increases on lands currently being cropped, this increase in crop production would be supplied by conversion of drylands. These drylands will be poorly suited for cropping, owing to thin, rocky soils on steep slopes, and low, variable, and unpredictable precipitation. A high rate of crop failure on such lands makes them susceptible to soil erosion and subject to high rates of abandonment.

The world food economy is being driven by continuing dietary shifts toward consumption of meat products. However, this shift will affect drylands differently than in the past. Impacts of the late nineteenth and early twentieth centuries were typically the result of excessive livestock stocking rates. The current settings and drivers are different. Given the saturation of per capita meat demand in developed countries, fewer livestock will graze drylands of Australia, North America, and Europe. Concurrently, as seen in recent decades, livestock numbers will continue to increase on the Asian and African continents where per capita meat demand continues to increase, although likely at a decelerated rate in coming decades. However, the demand for meat will be increasingly serviced by swine and poultry, and these more intensive livestock production systems will require increased reliance on and production of cereal grains. This demand for grains will drive conversion of drylands to cropland agriculture, and will place additional land area at risk for desertification. Reliance on traditional free-ranging livestock production systems will continue to decline, and will lead to shifts in the valuation of drylands for supplying other goods and services.

These shifting land uses represent opportunities to enhance the supply of other goods and services, but will require increased attention to valuing goods and services other than traditional food and fiber production. An often overlooked requirement of this valuation will be the need for methods to accurately assess benefits that result when management practices change to enhance the supply of these alternative goods and services.

4.20.2.3 Supporting Services

4.20.2.3.1 Plant Production, Carbon and Nitrogen Cycling

Primary production is a central process in the functioning of an ecosystem by which plants capture energy coming from the sun and transform it into chemical energy for microorganisms, animals, and humans. The flow of energy from the sun and back to outer space is coupled to the carbon cycle in most ecosystems. Plants capture carbon dioxide from the atmosphere and convert it to chemical energy (carbon based compounds, called carbohydrates) using light energy from the sun along with water and soil nutrients. This process is known as photosynthesis in plants, and the measurement of its magnitude represents ‘primary production’ in ecosystems. Primary production is estimated by assessing changes in plant mass over a known period of time (weight of biomass per unit area of land per unit of time (e.g., kg/ha/year)).

In drylands, plant production is limited by water availability, and nitrogen (N) is the second most important limiting factor. Average annual plant production increases with annual precipitation across a range of grasslands and shrublands located throughout the central and western United States. Dryland ecosystems with extremely low precipitation are most frequently limited by water availability, except during short periods of time after precipitation events when they can become limited by N availability. Water and N cycles are closely linked because their availability controls the activity of microorganisms and plants, which are sources and sinks of reactive N. However, the response of plants and microbes to water availability is not in synchrony because of their differential sensitivity to water availability (Schwinning and Sala 2004). For example, droughts negatively affect plant uptake more than they affect microbial mineralization. Thus, during dry periods, arid ecosystems tend to accumulate nitrate, which is one of the most common forms of mineral N in soils. During wet periods, however, mineral N concentration in soils is lower than in dry periods mostly as a result of increased demand by actively growing plants.

Primary production is a supporting ecosystem service (**Figure 1**) necessary for the production of all other services. Humans benefit from primary production indirectly because provisioning, regulating, and cultural services depend on it. In drylands, the major provisioning service is food production, and the growth of livestock and wild animals upon which humans depend is directly related to the abundance of plant biomass or primary production, and is related to forage production (see Section 4.20.2.2.2). Similarly, most regulating services depend on primary production that affects plant cover of the land surface, which in turn affects albedo and water balance and thus regulates climate (**Figures 2 and 3**; see Section 4.20.2.1.1). Primary production also affects disease regulation (see Section 4.20.2.3.5). For example, increased fall–spring precipitation associated with the El Niño phenomenon results in an increase in primary production in the American Southwest that leads to an explosion of deer mice (Peromyscus spp.), the rodent vector of the hantavirus (Yates et al. 2002). Primary production directly affects carbon sequestration (see Section 4.20.2.1.2) because it represents the major input of organic carbon into the relatively stable soil organic matter pool. Respiration of plant roots and decomposition of plant material provide the CO_2 needed to form pedogenic carbonates, which are a strong C sink in drylands (see Section 4.20.2.1.2).

Consequences of Desertification for Plant Production

Primary production is a relatively resilient ecosystem supporting service. However, even subtle changes in the nature of primary production can have major impacts on provisioning and regulating services. Desertification affects provisioning ecosystem services, such as food production, first by changes in species composition and species abundance. A replacement of palatable and grazing sensitive species by unpalatable, grazing resistant species has a relatively small effect on primary production (Peters et al. 2011), but may have a disproportionately larger effect on livestock production (Fredrickson et al. 1998). Grazing of herbaceous plants is often accompanied by the encroachment of unpalatable shrubs that feed back to reduce forage, and hence livestock production. In cases where perennial herbaceous plants give way to annual plants, production becomes less predictable and confined to narrow windows of time that correspond to the short life-span of annual plants (weeks to months). These short bursts of productivity can reduce soil water and nutrients needed by perennial plants that can be competitively displaced from the ecosystem. Furthermore, these annual plants produce far more biomass than animals can consume. When they complete their life cycle and die, they generate large amounts of fine, dry litter that is highly combustible. This increase in litter can dramatically alter the fire regime compared to historic levels (see Section 4.20.2.3.3). Grazing-induced reductions in perennial plant productivity and cover also expose the soil surface to erosional forces that then feed back to further accentuate degradation (see Sections 4.20.2.1.1 and 4.20.2.3.2). Erosion of the soil by wind caused by human activities and desertification processes that cause emission of nutrient-rich dust particles have the potential to change the biogeochemical properties of soils by reducing fertility (e.g., Okin et al. 2001; Neff et al. 2005; Li et al. 2007).

Planting of non-native grasses to restore desertified grasslands and improve forage production for livestock has been a long tradition in the drylands of North America. The US Department of Agriculture has maintained active research programs aimed at screening, breeding, propagating, and introducing plant materials collected from other parts of the world. In the Southwest United States, perennial grasses from Africa, notably Lehmann lovegrass and buffelgrass, were widely planted in the mid- to late 1900s. Since that time, they have expanded spatially to the point where they now threaten biodiversity across much of the region (see Section 4.20.2.3.4).

Threats to Future Trends in Plant Production

Because plant production is governed by both water and nitrogen, changes in one or both of these drivers in the future would impact patterns in production and the services that depend on it. Directional decreases in precipitation, such as an increase in the frequency, intensity, and duration of drought, would result in decreases in plant production. These decreases would be particularly so for perennial grasses and would likely make additional areas susceptible to shrub invasion and desertification (Fredrickson et al. 1998). Increases in precipitation, combined with sustained livestock grazing, would accentuate effects of dry periods on transitions from grasslands to shrublands. By contrast, directional increases in precipitation may have unexpected effects in shrublands that are commonly perceived as highly resistant to change. A 5-year wet period resulted in a nonlinear increase in grass production in shrublands as a result of grass seedling establishment and growth (Peters et al. 2011). Because large grass production was maintained even in subsequent dry years, this wet period may have initiated a state change reversal from shrublands to grasslands that has not been observed over the past 150 years. Subsequent wet periods are expected to result in similar state change reversals. Increase in nitrogen to these systems from atmospheric deposition would also favor grasses that are currently nitrogen limited, compared with shrubs, such as mesquite that can fix their own nitrogen.

Clearly, changes in land use have effects on regional climate (Pielke et al. 2011; Avila et al. 2012), as well as effects on plant production. Although conversion of grazing land to agricultural land through water redistribution may have positive short-term effects on plant production, the long-term impacts on water quality and quantity, and trade-offs with increasing human demands for water (see Section 4.20.2.2.1) may limit the feasibility of these land conversions in the future.

4.20.2.3.2 Air Quality

Air quality impacts all inhabitants of dryland regions. The atmosphere is comprised of gases, as well as, very small solid or liquid particles known as aerosols. One of the most obvious aspects of air quality is visibility, which is a function of both the amount and type of aerosols in the air. The most important contributor to low visibility in drylands is mineral dust, which is produced when strong winds strip particles from non-vegetated surfaces in the landscape, and a portion of those particles become suspended in the air column (Okin et al. 2006). Large dust storms result in significant reductions in visibility, and create hazards to both air and road travel (**Figure** 4(c)). Reports of major traffic accidents along roads and highways are common from dryland regions. Dust can also contribute significantly to vehicle and aircraft maintenance costs.

Dust can have a profound impact on human health (see Section 4.20.2.3.5). For instance, Coccidioidomycosis (known as valley fever) is a sometimes fatal disease caused by a fungus endemic to the American Southwest that is transported on dust (e.g., Kolivras and Comrie 2003). Desert regions with significant dust can frequently violate health standards for respirable material (PM10 and PM2.5, particulate matter less than 10 μm and 2.5 μm, respectively), and desert dust has been positively linked to hospitalization of children due to asthma.

Consequences of Desertification for Air Quality

Desertification often leads to either a reduction in vegetation cover or a reorganization of that cover so that the size of unvegetated gaps and amount of bare ground between vegetation increases. These larger bare gaps are more prone to wind erosion and the dust emission that accompanies it. Unvegetated areas made directly by humans, whether roads, construction sites, or off-highway vehicle tracks, also contribute to dust emission, particularly when the disturbance is aligned with the prevailing wind direction. Soil surface disturbance of natural desert stabilizers (biological and physical crusts, desert pavements) due to agricultural, recreational, and grazing activities has resulted in large increases in dust production in the Southwestern United States since 1850 (Neff et al. 2008). Drought, by reducing plant cover and production (see Section 4.20.2.3.1), can also result in large bare areas and hence increased dust emission. Aerosols and gaseous components in smoke significantly impact air quality and can be linked, in some cases, to desertification. For instance, throughout much of the Sonoran Desert, shrub communities that evolved in the near-absence of fire are being invaded by warm-season grasses that can sustain high enough fuel loads to result in wildfire (see Section 4.20.2.3.3) (D'Antonio and Vitousek 1992). In these areas, smoke and gas emissions due to fire would have been, in the absence of this form of desertification, a rare occurrence. Dust emissions following these fires would be elevated until vegetation cover is restored.

Finally, many desert plants are known for having strong scents, a common indicator of the emission of volatile organic carbon (VOC) compounds from their leaf surfaces. Mesquite and creosote bush are common shrubs that have increased throughout the American Southwest with overgrazing by livestock and drought that led to broad-scale desertification. These shrubs are strong producers of VOCs compared with grasses. In their gas phase, VOCs from desert vegetation can contribute to anthropogenic emissions and lead to air quality standards being exceeded. Furthermore, VOCs can produce liquid aerosols that reduce visibility while enhancing the longevity of GHGs and radiative forcing (see Section 4.20.2.1.1).

Threats to Future Trends in Air Quality

The two largest threats to air quality in drylands in the future are changes in land use and possible changes to drier conditions. Changes in land use that increase bare ground on soils susceptible to wind erosion would undoubtedly create an increased frequency of poor air quality in drylands. Similarly, an increase in periods of drought that reduce vegetation cover would lead to an increased occurrence of dust emission events.

4.20.2.3.3 Disturbance Regimes: Wildfire

Wildland fire is commonly perceived as a threat to human life, property, and, in some cases, ecosystem services. Many people believe that fires should be prevented and, if they do occur, that rehabilitation and restoration actions may be warranted. It is less appreciated that fire historically played a major role in maintaining ecosystems in their current, natural, or otherwise desired condition (e.g., Johnston and Klick 2012). Ecosystems are affected by fire at various levels of intensity and patterns of burning (e.g., within and among years and across landscapes). The fire regime, or the magnitude, temporal, and spatial characteristics of fire, partially defines many ecosystems. Like many other agents of natural disturbance (e.g., extreme weather events, pest outbreaks), fire regimes can promote biodiversity, heterogeneity, and dynamic ecosystem stability. Fire regimes are also a very strong natural selection factor that influences the evolution and distribution of species. When fire regimes are altered, populations, communities, and ecosystems can be affected along with the services they provide.

Role of Fire in Desertification with Consequences for Ecosystem Services

Dryland ecosystems have a characteristic fire regime that both affect, and are affected by, the composition and structure of vegetation. In grasslands of the American Southwest, the pre-Anglo-European settlement fire regime was one of moderate intensity surface fires carried by perennial grasses in late summer when plants were dormant and primary production (see Section 4.20.2.3.1) was at its peak 28 (**Figure** 4(d)) (McPherson 1997). Livestock grazing beginning in the mid-1800s, and landscape fragmentation and fire suppression activities during the mid- to late 1900s, reduced the amount and continuity of grass fuels and hence the frequency and extent of fires (Allen, 2007). With less fire, woody species expanded into areas where frequent fire previously excluded them, resulting in a decline in grasslands and an increase in areal extent of shrublands. As woody plant abundance increased, grass production further decreased, while bare ground increased, further reducing the probability that fire would start and spread, thus providing a positive feedback that reinforced the maintenance or increase in woody plant abundance (Ravi et al. 2007). The replacement of grasslands by shrublands following cessation of fire in drylands results in lower levels of primary production (see Section 4.20.2.3.1), lower carbon sequestration potential (see Section 4.20.2.1.2), and higher cover of bare ground; all of which feed back to influence the region's climate (see Section 4.20.2.1.1) and impact air and water (see Sections 4.20.2.2.1 and 4.20.2.3.2) resources.

By contrast, shrublands and savannas were historically characterized by less frequent and patchier fires compared to grasslands. Longer intervals between fires allowed shrubs and trees to establish and grow sufficiently large to survive surface fires. Removal of fine fuels by livestock grazing and suppression of fire had less dramatic effects on these fire regimes.

Threats to Future Fire Regimes

Fire alone may not be sufficient to maintain native perennial grasslands under all conditions. Fire regimes depend on fine-fuel production by grasses, and influence the capacity for grasslands to persist only if livestock grazing regimes, soils, and climate are conducive to the establishment and growth of perennial grasses. Threats associated with desertification that affect soil fertility and the distribution of soil nutrients, or that result in reduced soil moisture levels during the summer, can reduce grass productivity and cover, thus reducing fire frequency and intensity, and increasing the chances of woody plant encroachment.

Similarly, soil nutrient loss and horizontal homogenization in shrublands invaded by non-native grasses may prevent re-establishment of shrubs. Changes in the amount and season of lightning can also affect the frequency and seasonality of fire, and the balance of grasses versus woody plants. Landscape fragmentation can isolate patches of fuels, and limit the size and spread of wildfires; thus muting the potentially positive effects in maintaining grassland or negative effects in maintaining shrub steppe and woodlands. However, fragmentation may also facilitate the application of prescribed fire during the summer season by providing pre-established fuel breaks that make individual fires easier to manage. Increased nitrogen deposition and elevated concentrations of atmospheric carbon dioxide can promote the establishment and dominance of non-native plant species, which can affect fire regimes if they alter the structural and seasonal characteristics of fuels (Brooks et al. 2004).

In addition, invasions by non-native grass species have had tremendous effects on fire regimes. Non-native perennial grasses, such as Lehmann lovegrass and buffelgrass, and annual grasses, such as red brome, have increased the mass and continuity of fuels and decreased the time required for post fire fuels to return to conditions that can carry subsequent fire. These changes have increased the frequency and extent of fires in shrub steppe such that native woody species cannot persist and non-native grasslands now predominate. These conversions of vegetation types and fire regimes have concomitant negative effects on individual species and overall biodiversity (Ravi et al. 2009).

4.20.2.3.4 Biodiversity

Biodiversity refers to the range of variation found among microorganisms, plants, fungi, and animals. Biodiversity is typically measured using numbers of species in an area and how rapidly the identity of species changes over space and time. Biodiversity indirectly affects ecosystem processes, such as net primary production (see Section 4.20.2.3.1), decomposition (see Section 4.20.2.1.2), biological control of pests (see Section 4.20.2.3.5), and even physical processes affected by plants such as water and wind-driven soil erosion (see Sections 4.20.2.2.1 and 4.20.2.3.2). Biodiversity is also an important basis for sustenance, recreation, and spirituality for people who inhabit or visit drylands. Stakeholders with direct interests in biodiversity include hunters, naturalists, tourists, exurban homeowners, and ranchers. These stakeholders may have differing values for particular species comprising biodiversity, including species that are: game (mule deer, scaled quail), threatened with extinction (Chiricahua leopard frog, Chihuahua Scurfpea), pests (coyotes, woodrats, certain shrubs), regulators of ecosystem processes (termites, grasses), or recreation (native birds, wildflowers). These varying values guide how biodiversity is managed in drylands (see Section 4.20.2.4.1).

Consequences of Desertification for Biodiversity

Biodiversity in drylands is strongly influenced by the high variability in stress (e.g., temperature) and resource availability (e.g., water and plant production) over time and space, particularly when compared with other ecosystem types (Stafford Smith and McAllister 2008). Dryland species often have specific adaptations that allow them to tolerate or avoid resource scarcity and stress, and certain species are highly specialized to particular conditions. Land uses, including variations in grazing pressure, conversion of wildlands or rangelands to crop agriculture, and urbanization interact with environmental variability and species adaptations to cause changes in biodiversity. Of particular concern, desertification associated with past heavy livestock grazing has reduced grassland associated species when shrubs or bare ground dominate ecosystems (Archer 2010; Eldridge et al. 2011). Similarly, historically shrub-dominated ecosystems and their associated flora, fauna, and microorganisms were altered when invasive annual grasses become dominant (Ravi et al. 2009). In such cases, biodiversity of a specific functional group of organisms (e.g., ants or breeding birds) may be reduced or the identity of species may change with no net loss of species numbers at a local scale (**Figure 5**(a)). Often, however, certain species decline in abundance, so these species become the focus of biodiversity concerns and management efforts (**Figure 5**(b)).

Threats to Future Trends in Biodiversity

In general, the extensive loss of formerly widespread habitat types due to past agricultural practices or non-native species invasions focuses management attention on the preservation and restoration of currently rare habitat types and their dependent species, such as reducing shrub cover to promote open perennial grasslands in the Southwestern United States (Archer et al. 2011). New challenges to rare habitat types in drylands are also emerging, including increasing aridity, and solar and wind energy development that is increasingly focused in drylands, and conversion of the more humid portions of drylands to crop agriculture (see Section 4.20.2.2.2). Mapping, model-based forecasting, careful land-use planning, and monitoring will need to be carefully coordinated as such novel conditions expand in order to prevent the additional loss of biodiversity elements.

4.20.2.3.5 Disease, Pests, Pathogens

The fate of disease in a changing environment is a significant and complex question for scientists and decision-makers alike. For human disease, outbreaks and altered patterns of disease are linked to both biophysical and social factors as part of coupled natural-human systems. Infectious diseases, those that are transmissible and caused by pathogens such as viruses, bacteria, fungi, protozoa and parasites, are particularly susceptible to interactions between ecosystems and human-related changes in land use and cover. Often, these pathogens are associated with a vector species that is part of the transmission cycle. Diseases and human health issues of particular importance in the American Southwest include valley fever (*Coccidioidomycosis*), Hantavirus, plague, and West Nile virus.

Consequences of Desertification to Disease, Pests, and Pathogens

Disease and its outbreaks can be depicted in an epidemiological triangle, comprising the environment (e.g., habitat, climate), a host (e.g., humans), and a pathogen (e.g., malaria parasite). Where applicable, the middle of the triangle includes a vector (e.g., mosquito, rodents, and ticks) that connects all three points of the triangle (Comrie 2007). The impacts of planned or unforeseen interactions among natural and human systems can alter relations across the triangle. Amplified disease threats can

Figure 5 Biodiversity can be increased, decreased, or unchanged with desertification that depends on focal species of interest: (a) pronghorns (*Antilocapra americana*) at the USDA ARS, Jornada Experimental Range, USA, are considered of 'least concern' by the IUCN red list of threatened species, and (b) banner-tailed kangaroo rats (*Dipodomys spectabilis*) are ecosystem engineers of the native grasslands in the American Southwest that are considered 'near threatened' by the IUCN red list of threatened species as a result of desertification and shrub invasion. Photos credit: Andrea Campanella (New Mexico state University).

occur through new combinations of suitable conditions (e.g., restricted vector habitat, urbanization) leading to increases in the pathogen or vector populations or via greater host exposure. Importantly, disease outbreaks can also occur if key regulating services provided by the ecosystem (**Figure 1**) are diminished (Irwin and Ranganathan 2007). For example, desertification can change surface water availability, abundance of mosquito predators, and temperature, all of which affect the effectiveness of the mosquito as a disease vector.

Several kinds of regulating services provided by ecosystems are relevant to disease and pathogens in drylands. For example, riparian systems promote clean water by acting as a biofilter for fecal pathogens in streams that cause waterborne diseases. Ecosystems generally have checks and balances in place where predators maintain populations of vector species in dynamic equilibrium. These balances can be upset by processes such as desertification (MEA 2005). Thus, a reduction in regulating ecosystem services can create conditions that lead to proliferation of vectors as pests (e.g., ticks, rodents, and mosquitoes) and the pathogens they carry.

Vectors and pathogens often create problems that result from the proximity of humans to locations where regulating ecosystem services have been diminished or removed. Urban areas provide the most prominent set of examples where highly altered, simplified, or exotic ecosystems cannot self-regulate in natural ways. For example, mosquito habitat in cities is often associated with water for irrigation or rainwater that collects in and around human habitation. Because mosquitoes in these environments are not part of a naturally regulated ecosystem, the potential for unchecked growth in vector populations is large. A complementary example is human exposure to Hantavirus, where rodent populations surge following high rainfall and abundant food supply (Yates et al. 2002). In subsequent average or dry years, human exposure to the virus increases as infected rodents seek food close to human dwellings.

Threats (or Opportunities) to Future Trends in Disease, Pests, and Pathogens

The biggest opportunities for the spread of disease at local scales are from landscape changes that modify the habitat for pathogens and their vectors. At regional and continental scales, the range of pathogens and vectors is associated with extremes of temperature and precipitation (Comrie 2007), such as frosts or changes in timing and duration of wet–dry spells. An example is dengue fever, currently in northern Mexico, but not yet in the Southwestern United States. The mosquito vector *Aedes aegypti* is present in the Southwest, but the pathogen is not endemic. It is unknown whether dengue will expand northward if the region's temperature and moisture environments change. The trajectory for these kinds of shifts in ecosystem services is inherently complex, and depends on changes in human activity, as well as the biophysical impacts of desertification within the climate system.

4.20.2.4 Cultural Services

4.20.2.4.1 Esthetics and Recreation

Non-material benefits obtained from ecosystems represent cultural services (e.g., esthetic and recreational experiences, cultural heritage, sense of place; **Figure 1**). Cultural services include and are shaped by human perceptions and preferences, recreational experiences, interpersonal displacement, and tolerance levels, and conflicts and benefits accrued to individuals in a landscape. Human evolutionary history has instilled strong adaptive biases that influence current perceptions and preferences with respect to visual landscapes and biological needs (Ulrich 1977). These adaptive biases and bonds between humans and their environment are strong and inherited, and are the basis for the proposition that esthetic satisfaction stems from the spontaneous perception of, and interaction with, landscape features. Explicit inclusion of cultural services is thus a key, but under appreciated, component of effective natural resources monitoring and management.

Cultural services have intrinsic value but also play a central role in determining the ecosystems, which people are disposed to value and protect, or to degrade or develop for other purposes. Perceptions of cultural services can be an important, albeit intangible, factor in public support of resource use, management, and policy. Alternatively, landscape or social conditions can change to have negative effects on desired cultural services that lead to undesirable conditions, declining recreation experience levels, conflicts among stakeholders, and eventually degraded environmental conditions. For example, increasing use in Saguaro National Park (Arizona) with associated physical impacts and competition between recreational groups (horse riders and hikers) diminished the recreation experience for each group and forced land managers to close trails, thus resulting in reduced opportunities.

Cultural ecosystems services are less understood and explored than other services, and are more difficult to quantify. Cultural services provide for human physical, mental, spiritual, social, cultural, and economic well-being, all of which are determined by a variety of traditional and changing perceptions, beliefs, attitudes, behaviors, needs, values, and influences. The provision of cultural services must take into account past, present, and possible future influences of humans on ecosystems.

Cultural services depend heavily on the relationship between humans and their environments. Recreational experience, for example, requires landscape settings that meet certain expectations in terms of the services they provide. Landscape settings such as lakes, meadows, and mountains provide unique experience opportunities, and humans are linked to each setting for a variety of reasons. Wildlands provide opportunities to explore and engage in nature, and to derive historic, spiritual, esthetic, and educational values. Cultural services in wildlands are observed in different ways: backpackers seek solitude, commercial outfitters earn income, mountain climbers seek danger and risk, and naturalists derive satisfaction from seeing and identifying plants and animals. Ecosystems providing cultural services also generate broader public support for conservation management. For example, the Cabeza Prieta Wilderness Area is Arizona's largest wilderness area, but is visited by very few humans. This primitive wilderness area is a symbolic refuge of nature that some suggest should be preserved and protected for inherent ecological, esthetic, and symbolic value. There is cultural value to many in knowing this type of landscape continues to exist.

Consequences of Desertification for Cultural Ecosystem Services

If desertification continues, there would be dramatic threats to the quantity and quality of cultural services available in drylands. With changing biodiversity (see Section 4.20.2.3.4 Biodiversity), the loss of wildflower production could result in lost recreation opportunities and the overall quality of the recreation experience. Increased human-related impacts, such as social trail and recreation site impacts would provide increased opportunities for invasive and non-native plant species.

Threats and the Future of Esthetics and Recreation

Significant threats to cultural services are associated with human use impacts and reductions in recreation opportunities. High quality recreation experiences often decline with increasing human population densities. Crowding, excessive numbers of visitors, and their associated impacts coupled with harsher environmental conditions affect the ability of these systems to sustain cultural services. For example, increased human use along the US – Mexican border in Organ Pipe National Monument in the Sonoran Desert, Arizona, has already led to a proliferation of trails and traffic on these fragile landscapes (**Figure 6**) (Sharp and Gimblett 2009). An increase in temperature and water stress on plants and animals would exacerbate the degradation from current human-caused impacts. The extent and severity of impact in disturbance-sensitive drylands suggest some of these environments may never recover (Sharp and Gimblett 2009). Climate impacts cultural services: weather influences visitor experiences and affects recreation choices, utility maximization, and net amenity benefits. Summer and winter season lengths determine the availability and quality of certain recreation opportunities, such as hunting, fishing, bird watching, and scenic viewing.

A critical challenge will be to provide cultural services, while at the same time balancing the protection of rapidly changing, declining, or degrading natural resources. A clear set of management objectives will be needed within the context of the many environmental changes underway (Cole et al. 2008). A more holistic paradigm that explicitly identifies and comprehensively incorporates cultural services is required. One such approach

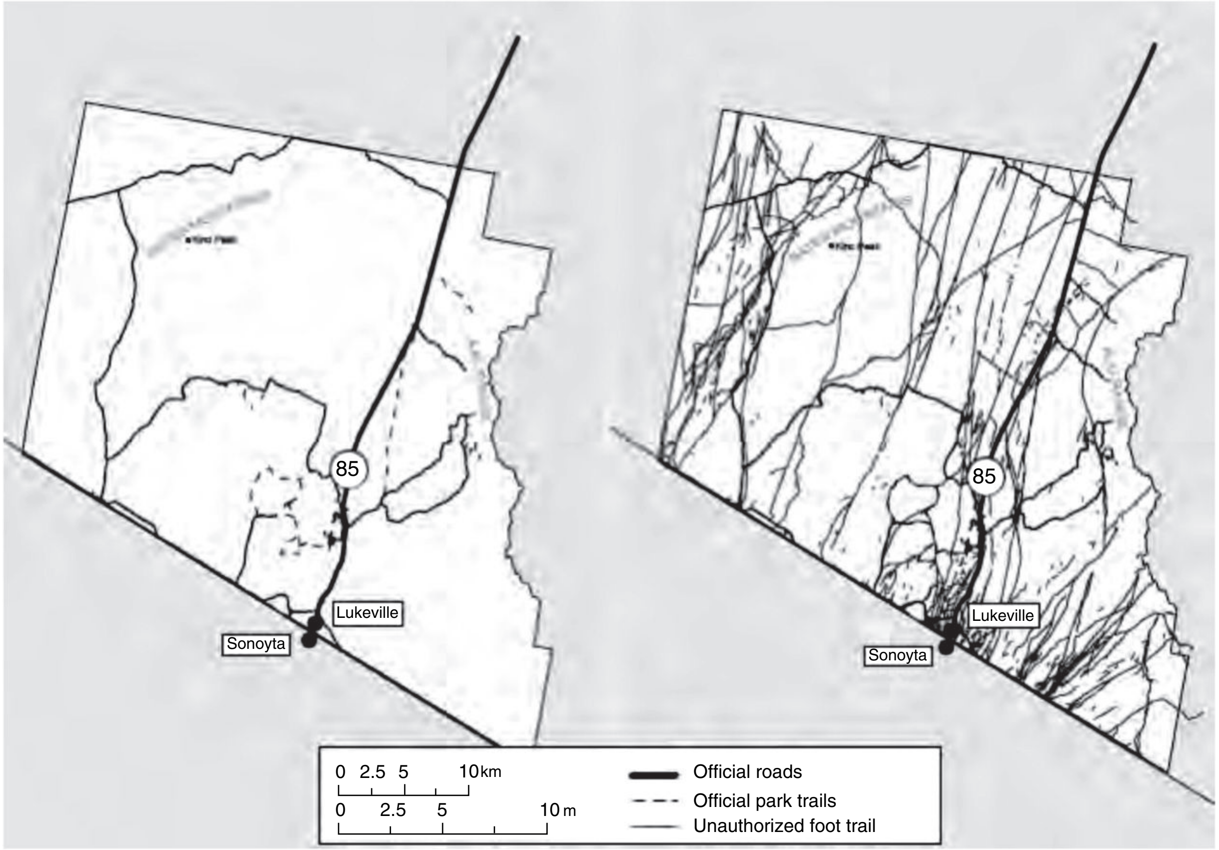


Figure 6 Increased human use along the US – Mexican border in Organ Pipe National Monument in the Sonoran Desert has led to a proliferation of trails and traffic on an already stressed landscape. Left: Official roads and recreational trails within Organ Pipe Cactus National Monument boundaries. Right: Official routes overlain with unauthorized routes that have resulted in severe loss of vegetation, erosion, unnecessary widening, gullying throughout Organ Pipe. These unauthorized routes will take years, if ever, to recover from such impacts. From Sharp, C., and R. Gimblett, 2009: Assessing border-related human impacts at organ pipe cactus national monument. *Conservation of Shared Environments: Learning from the United States and Mexico*, L. Lopez-Hoffman, E. D. McGovern, R. G. Vardy, and K. W. Flessa, Eds., University of Arizona Press, 226–40. (Permission granted from University of Arizona Press to publish figure: 12-1-2011.)

couples human and natural systems to rules governing land-use decisions, ecological models of landscape change, and decision support systems mimicking local landowners, recreational users, and resource management agencies (Scott et al. 2010a,b). This ongoing project attempts to understand complex utilitarian processes in human-dominated, semi-arid river systems and seeks to define the linked influences of climate, hydrology, societal practices and esthetic values, and any changes over time – on the social and ecological resilience of riparian corridors of two desert river systems: the Rio Sonora in Mexico and the San Pedro River, which originates at the same watershed boundary in Mexico, but flows northward into Arizona. Improved understanding of these complex processes provides a foundation for exploring what types of human occupancy and resource use may be possible, given climatic constraints set by a semi-arid ecosystem. In emphasizing the riparian-corridor ecotone, this project is exploring the nature and extent of combined societal and hydro-ecological changes under differing scenarios.

Public lands and protected areas, in general, are receiving a greater level and diversity of human activities and total visitation use than in historical times. This increase in demand leads to the question of whether public lands will have the ability to provide high quality cultural services now and into the future. Maintaining high quality cultural services, while protecting ecosystem integrity, remains at the heart of many contentious, confrontational, and highly scrutinized land-use planning and management processes that will continue into the future.

4.20.3 Potential Actions for Mitigation

4.20.3.1 Can Payments for Ecosystem Services Mitigate Desertification?

The growing awareness of the value of ecosystem services to society, and the increasing concern about threats to their continued provisioning, is catalyzing a new paradigm – viewing ecosystems as assets to be managed. As discussed above, drylands in the American Southwest provide a diverse array of services that support human life, food and fiber, clean drinking water, climate regulation, recreational experiences, wildlife habitat, and others (Havstad et al. 2008; Skaggs 2008). With the notable exceptions of food and fiber, the rest are public goods that have remained largely outside economic markets. Historically, the Farm Bill and other government programs have provided incentives to landowners for the protection of public goods. In the last decade, more and more conservationists, landowners, and natural resource managers are considering the concept of 'Payments for Ecosystem Services' (PES), as a way of providing market-based incentives to protect these goods. The objective of this section is to define PES and describe how it might be used to create incentives for preventing desertification and protecting the non-market goods provided by drylands. The questions addressed are: What types of PES programs are there and how they might be used to mitigate desertification? What are the short-term prospects for implementing PES programs in the American Southwest? And finally, given the vast public lands in the Southwest, how can PES be implemented on these lands? Payments for ecosystem services are market-based approaches in which users of ecosystem services directly compensate providers (i.e., landowners and managers) for their protection and supply. PES combines a positive incentive (if you improve and protect a resource, you can get paid by others to do so), with a negative incentive (if you impact a resource, you must or should pay for it) (Goldstein et al. 2011). Further, PES places the responsibility to pay for and protect ecosystem services on the individuals and private sector entities using the services. Ideally, PES should create payments for measurable outcomes (e.g., tons of carbon dioxide sequestered, volume erosion reduced, acreage of invasive vegetation removed) in contrast to government programs that provide incentives for changing management practices (e.g., grants for installing a fence to protect a waterway (CEAP 2011; Briske 2011)).

There are four types of PES programs that could be used to minimize or mitigate desertification in Southwestern grasslands. First, carbon programs provide payments to landowners and managers for undertaking management practices that reduce the loss of plant and soil carbon stocks (see Section 4.20.2.1.2). Second, water programs pay both upstream private landowners and public land managers for controlling erosion and grazing in order to promote higher air quality (see Section 4.20.2.3.2) and increase the quality and quantity of water delivered downstream (see Section 4.20.2.2.1). Third, biodiversity programs provide payments to landowners for the protection and/or restoration of a specified amount of habitat for target species (see Section 4.20.2.3.4) – such practices could include actions to mitigate desertification. Finally, there are bundled payments that combine carbon, water, and biodiversity benefits.

All programs require one of three market vehicles. First, compliance markets are created by regulation (e.g., Endangered Species Act, Clean Water Act). Second, voluntary markets occur when entities participate of their own volition – typically businesses to burnish a 'green' corporate image or private groups wishing to become 'carbon neutral.' Third, government-mediated payment programs (e.g., Farm Bill) use public funds to pay landowners for protecting or enhancing ecosystem services.

4.20.3.2 What Are the Prospects for PES in the US Southwest?

Despite the keen interest around the world in implementing PES programs, there are very few examples in arid regions and fewer yet in the Southwestern United States (Goldstein et al. 2011). Several years ago, observers of PES likely would have considered carbon programs to offer the greatest promise. However, failure to enact cap and trade (a federal regulatory driver for a nation-wide carbon offset program) led to the closures of the Chicago Climate Exchange in 2010 and its Sustainably Managed Rangeland Soil Carbon Sequestration Offset Project (Gosnell et al. 2011). Biodiversity markets in the form of mitigation banks to protect species habitat offer some promise: according to a recent report (Madsen et al. 2010), the habitat of at least 119 species in the United States is protected by mitigation banks. Arguably, the greatest promise for the Southwest lies in water programs, where municipal utilities enter into contractual agreements with upstream landowners or managers. An example of the potential for PES to align the interests of ecosystem service users and public land managers is the recently formed partnership between Denver Water, the utility that serves the city and surrounding suburbs, and the US Forest Service. Denver Water recently entered into a 5-year, $33 million partnership with the Forest Service to fund erosion control and wildfire prevention activities in its publicly managed upstream watershed. While some have questioned why the utility should pay a federal agency, the organizations argue that Denver Water is paying for additional land management practices specifically designed to protect and enhance water quality. Similar programs have been discussed in locations in the Southwest.

To date, there are few concrete examples of PES being used to combat desertification and degradation of drylands in the Southwest. In the absence of federal regulation on greenhouse gas emissions, it seems unlikely that carbon markets will emerge as a tool to mitigate dryland degradation, though state-level efforts (particularly in California) are continuing to keep some opportunities open. As biodiversity and water-based PES programs expand across the United States, it will be important for all stakeholders, land managers, private owners, civil society, and academia to carefully evaluate the opportunities that PES provides, and to tailor programs to meet the interconnected goals of preventing and mitigating desertification with protecting ecosystem services.

4.20.4 Recommendations for Land Managers, Policymakers, and Other Stakeholders

The effects of desertification and the threat of future effects upon ecosystem goods and services provided by drylands have important implications and lessons for land managers, policymakers, and other stakeholders who can be impacted. At the center of these implications is the knowledge that using general principles, even if derived from thorough research and peer reviewed analyses, will have limited application to any specific landscape and any specific emerging threat to any combination of goods and services. Actual management practices applied or policies implemented will have to be contextualized to the specifics of a landscape. For example, research may have identified the typical capacity of an ecosystem to produce a sustainable level of a particular good, such as livestock products. However, the vagaries of climatic drivers and resulting primary production for a particular ecosystem will negate the application of that average capacity to any specific time frame. In addition, generalizations based on past or recent research and experience may be irrelevant for ‘novel ecosystems’ developing under future conditions. Management programs need to be agile. Management actions need to be increasingly adaptive, and the policies supporting or constraining those actions need to be sufficiently flexible to readily accommodate adaptive adjustments.

Recognition of the need for adaptive management and flexible policies impacts the general principles that guide management. In the past, extraction of combinations of goods and services from drylands was guided by the principles of proper limits to use by livestock, proper distribution and timing of this use across landscapes, and proper types of livestock matched to a landscape and its forages. However, specific uses and combinations of uses change over time. Reductionist science has serious limits in identifying proper uses and combinations of uses for all landscapes in dynamic environments with numerous changing and interacting drivers. These principles, employed ineffectively on all continents for the past century, now need to be replaced.

Principles guiding resource managers need to be based on the simple concept that the central element to all of these goods and services, threatened or not, is the basic commodity of land. Within this concept is the recognition that ‘land’ is heterogeneous on many levels, and management principles and policies need to be designed and implemented based on this knowledge. The principles guiding management actions and policies should be rooted in the technology that classifies land based on similarities and differences with respect to climate, soil, landscape position, prior histories of management, and inherent vegetation dynamics – the ecological site and its description (Bestelmeyer et al. 2009). The cardinal principles of land management are then the proper descriptions of a site’s (1) potential to provide goods and services (which may be predicated on prior history), (2) current status, (3) suite of possible future trajectories in response to management practices and environmental conditions, and (4) monitored responses to those practices and conditions. These principles are very different than those utilized in the past, and the prior principles certainly contributed to the threatened and degraded conditions currently in existence.

Two key issues emerge from the recognition of the need for a new set of guiding principles. First, the successful application of these principles requires that institutions of management and policy improve their ability to learn from and adapt to the information derived from site-specific responses. Management practices, and the policies that guide them, need to be redesigned to dynamically accommodate specific lessons learned. These institutions need mechanisms where they can be informed by data and associated analyses. These mechanisms will require that landscapes have diverse and detailed data layers that are accessible, transparent, timely, and suitably described by metadata (Peters 2010). The infrastructure to support data-informed management actions and policies is not yet appropriately interactive and integrative, but these barriers can be overcome.

Second, conducting science to collect and organize data to inform land management and policy will require considerably different methodologies than used in the past. Issues related to climate change and desertification have forced ecologists and most resource managers to quantify patterns and processes at spatial scales more extensive than those addressed previously: how landscapes, land surfaces, and the atmosphere interact across a broad range of scales. This new science includes, but goes far beyond, the traditional highly controlled experimental designs of our reductionist past. It recognizes the need for research to (1) span multiple levels of organization in ecological hierarchies (reductionist approach) balanced by research aimed at understanding how mechanisms and processes at a given scale play out at broader scales over longer times (holistic approach), and (2) be interdisciplinary. For example, it has been stated that soil science has been “brilliantly informed by reductionist physics and chemistry, poorly informed by biology, ecology and geography, and largely uniformed by the social sciences” (Swift 1999). The science challenge now is less controlled, much more variable, and yet much more applied (Sayre et al. 2012). It is a science that employs management as an experimental, hypothesis-testing tool, e.g., the scientific method is applied in the testing of the effects of management practices as they are applied, or have been applied, in the field. It is a science that provides the types of data that can inform both management actions and policies geared toward heterogeneous landscapes under dynamic drivers, and that can learn and adapt as conditions warrant.

Finally, given the uncertainty of future climatic conditions, continued spread of exotic organisms, increasing global demand for an array of goods and services, and impacts of other drivers, it is important that policy makers and managers maintain and utilize mechanisms that can inform and focus science priorities. One possible mechanism to employ is future plausible scenarios generated by science-based models, worst-case historical and recent paleo–conditions, and sequences of events developed from linking together subsets of extreme events (such as the two most extreme droughts in the historical record placed in sequence). This mechanism can both prepare and direct management and policy actions. These scenarios can then be refined and employed in management and policy, and thus serve to maintain communication among scientists, policy makers, and managers relative to information needs and their relevance to the emerging problems of the future. A key recommendation for policy makers and managers is to more strongly employ and maintain linkages with scientists in shaping and focusing their priorities and their hypotheses to be tested.

4.20.5 Summary

Desertification, the broad-scale conversion of perennial grasslands to dominance by annual plants or xerophytic shrubs, and the attendant consequences to ecosystem services, has affected arid and semi-arid regions globally over the past several centuries. This state change is expected to continue in the future. It is generally well recognized that desertification is a cumulative threat that explicitly includes both climatic (e.g., drought) and land-use drivers (e.g., livestock overgrazing and inappropriate conversions of rangeland to cropland). However, a basis for ranking the relative importance of these drivers is lacking for many locations. In addition, the emergence of additional drivers (e.g., non-native forbs and grasses) modifying historic fire regimes will result in even more complex dynamics in the future. Questions remain: (1) How do these multiple drivers interact through time and space to influence grass–shrub dynamics? (2) When is the region's climate versus land use expected to be the primary driver governing ecosystem dynamics? (3) Where are management actions expected to be the most effective given variability in climate? (4) How would specific ecosystem services be impacted, and (5) What are trade-offs in positive versus negative effects when considering bundles of services?

Clearly, climate can have unanticipated effects, in particular for dryland regions with low and variable precipitation and high temperatures in the growing season. However, any change in climate statistics would be operating across diverse landscapes that include a mosaic of human-dominated and natural states, each governed by different drivers and susceptible to different threats. Accounting for the separate and interactive effects of these threats on grassland–shrubland transitions will be necessary as we move forward into a difficult to predict, if not unknown, environmental world.

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4.21 Vulnerability of Coral Reefs

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Glossary

Additive effect A type of cumulative impact when the combined impact of multiple stressors is equal to the sum of the impacts of individual stressors.

Antagonism A nonadditive, mitigative interaction ('anti-synergy') between multiple stressors that occurs when the combined impact of these stressors is less than the sum of the impacts of individual stressors.

Community disassembly The process of nonrandom species losses and declines that can affect ecosystem structure and function.

Cotolerance The positive correlation between a species' tolerance to one stressor and its tolerance to another stressor that can reduce the cumulative impact of multiple stressors.

Recovery The ability of an ecosystem to 'bounce back' to a state that is functionally similar to its original state after a disturbance.

Resilience The capacity of an ecosystem to absorb disturbance without shifting to an alternative state and losing function and services. Resilience encompasses two separate processes resistance and recovery.

Resistance The immediate ability of an ecosystem to absorb disturbance without changing state or function.

Stressor Any environmental or biological impact that exceeds natural levels of variation to cause a negative ecological response.

Synergy A nonadditive interaction between multiple stressors where the combined impact of these stressors is greater than the sum of the individual impacts.

Coral reefs are among the most biodiverse ecosystems on the planet and provide immense ecological and economic benefits that contribute to the welfare of millions of people (Moberg and Folke 1999). However, coral reefs are also one of the most vulnerable ecosystems to climate change (Hughes et al. 2003, Hoegh-Guldberg et al. 2007). This may seem puzzling because modern scleractinian (reef-building) corals have experienced and survived extreme variation in ocean conditions (including multiple mass extinction events) since their appearance in the Middle Triassic, approximately 240 millions of years ago (Stanley 2003). However, the current climate-related coral reef crisis is unique for two reasons. First, the rates of increase in atmospheric carbon dioxide concentrations associated changes in carbonate availability, and seawater acidity are simply unprecedented (Knoll et al. 2007). Second, these rapid environmental changes are occurring against a background of other widespread human-induced disturbances, such as fishing, coastal runoff, pollution, and invasive species, which may ultimately stress corals to the brink of extinction (Carpenter et al. 2008).

Understanding the cumulative impacts of stress on ecosystems and rethinking our management philosophies to explicitly incorporate multiple, interacting stressors is a critical challenge for twenty-first century conservation (Paine et al. 1998). In this respect, coral reefs are unfortunately a model ecosystem to evaluate the cumulative impacts of multiple stressors and how to manage for them (Darling et al. 2010). In this chapter, we briefly review the impacts of climate change on coral reefs and consider how climate change-induced coral bleaching can interact with local, human-caused stressors affecting these species-rich ecosystems. Central to current thinking about the management of coral reefs is the concept of resilience. We outline the conventional view of coral reef resilience to climate change, and offer an alternative that considers how changes in coral community structure, resulting from local stressors, can affect resilience. Finally, we consider the implications of these two resilience frameworks for coral reef management and the role that no-take Marine Protected Areas (MPAs) can play in a changing climate. We conclude that there is hope for the survival of coral reefs. However, the cumulative impacts of climate change and local human impacts may motivate a new agenda for coral reef conservation.

4.21.1 Impacts of Climate Change on Coral Reefs

Increasing atmospheric CO_2 and climate change are warming and acidifying the world's oceans. This future 'hot and sour soup' (Palumbi 2010) will have widespread consequences for scleractinian corals (Hoegh-Guldberg et al. 2007). Over the past century, average global sea surface temperatures (SSTs) have risen by 0.6 °C and temperature anomalies, i.e., deviations from long-term temperature averages, are occurring more frequently (Hoegh-Guldberg 1999; Hoegh-Guldberg and Bruno 2010). Warmer than normal SSTs can result in coral bleaching, caused by a breakdown in the relationship between corals and the endosymbiotic unicellular algae (zooxanthellae) that provide corals with most of their metabolic requirements. Thermal stress can trigger the expulsion of the colorful zooxanthellae from their coral hosts, which can cause the coral to turn white or 'bleach' (Hoegh-Guldberg 1999). Corals may recover from short-term bleaching, by adopting new zooxanthellae, which are sometimes more thermally resistant than the ejected strain (Baker 2001 Baker et al. 2004; Berkelmans and Van Oppen 2006), but the physiological stress of bleaching interrupts coral growth, reproduction, and may make recovering corals more susceptible to diseases (Harvell et al. 2002; Bruno et al. 2007). Sustained SSTs 1 °C above average can lead to mass bleaching, which can affect hundreds to thousands of kilometers of reef area and result in widespread coral mortality (Hoegh-Guldberg 2005). The loss of live coral cover and architectural complexity on bleached reefs can have substantial ecological and economic consequences, affecting a broad range of coral reef fish, invertebrates, and the fisheries they support (Pratchett et al. 2008).

In addition to warming the oceans, climate change is fundamentally altering ocean chemistry. Approximately one-third of atmospheric CO_2 emissions are absorbed by the oceans and dissolve to reduce ocean pH, effectively increasing the acidity of seawater (Pelejero et al. 2010). Over the past 150 years, sea surface pH has dropped by 0.1 units and sea surface acidity has increased by ~26% (Doney et al. 2012). This altered ocean chemistry can reduce the ability of corals to build their calcium carbonate skeletons and can also disrupt critical metabolic processes, such as gas exchange and reproduction (Kleypas and Yates 2009; Pelejero et al. 2010). Ocean acidification can also decrease the productivity of calcifying crustose coralline algae, the preferred settlement substrate for juvenile corals, which may disrupt important cues for coral recruitment (Anthony et al. 2008; Doropoulos et al. 2012). Acidification is expected to broadly alter coral communities. A glimpse of such impacts is provided by 'champagne reefs,' such as those found in Papua New Guinea. These reefs persist in naturally acidic waters caused by the bubbling of carbon dioxide released from volcanic seeps in the substrate; the pH at acidic sites – around 7.8 – is consistent with some scenarios of ocean pH by the end of this century. The naturally lower pH reef communities are depauperate in coral diversity and have fewer structurally complex framework-building corals, less crustose coralline algae, fewer juvenile coral recruits, and a higher cover of fleshy macroalgae and seaweeds compared to adjacent reefs with 'normal' 8.1 pH (Fabricius et al. 2011). Thus, ocean acidification may profoundly affect the structure and function of coral reef benthic communities. Coral reef fishes will also be affected by altered ocean chemistry, if the results of laboratory and field experiments materialize in natural populations. For example, high CO_2 conditions can impair the cognitive and sensory abilities of juvenile fishes by interfering with neurotransmitter function (Nilsson et al. 2012), which can affect their settlement (Munday et al. 2009) and predator avoidance behavior (Dixson et al. 2010). Such altered behavior may drastically reduce juvenile survival and recruitment, which is expected to have wide-ranging consequences for the sustainability of fish populations in a more acidic ocean (Munday et al. 2010).

Ocean warming and acidification are only two of the many manifestations of climate change. Other potential influences include sea level rise and changes in storm regimes caused by warmer SSTs (Hoegh-Guldberg & Bruno 2010; Doney et al. 2012). However, these effects are expected to be more benign than the fundamental threats to coral survival posed by a warmer and more acidic ocean. Nevertheless, while climate change is an unprecedented threat, it is just one of many threats that jeopardize coral reefs.

4.21.2 Coral Reefs and Cumulative Impacts

In addition to climate change, coral reefs are impacted by a multiplicity of local stressors. These include fishing, which removes species with important ecological functions, sedimentation from coastal and watershed development, eutrophication from agricultural and urban runoff, and invasive species, which can outcompete or prey upon native species. More than half of the world's coral reefs are faced with high levels of human activities (Halpern et al. 2008). The cumulative impacts of local and global stressors have resulted in widespread losses of live coral cover (Gardner et al. 2003; Bruno and Selig 2007) and an elevated risk of extinction to one-third of all reef-building corals (Carpenter et al. 2008). Shifts have been observed in the structure and diversity of human-impacted coral communities (McClanahan et al. 2007a, 2007b; Alvarez-Filip et al. 2011), such as the flattening of coral reef habitats when architecturally complex coral species are gradually replaced by smaller, simpler taxa (Alvarez-Filip et al. 2009). Such fundamental changes in the reef framework can have cascading consequences for reef fish and invertebrate abundance and diversity, which depend on reef habitat for food and shelter (Graham et al. 2006; Pratchett et al. 2008; Messmer et al. 2011). The cumulative impacts of multiple stressors are undoubtedly already affecting the ecosystem functions and services of coral reefs, which are estimated to be worth more than $30 billion annually (Cesar et al. 2003). The impacts on tourism, coastal protection, and fisheries are the most obvious. For example, the 1998 mass coral bleaching event in the Indian Ocean resulted in an estimated $706 million to $8.2 billion in economic damages (Wilkinson et al. 1999). Intact coral reefs have high vertical relief, which effectively dissipates the wave energy reaching the coastline, protecting beaches and buildings from storm surges and tsunamis (Sheppard et al. 2005).

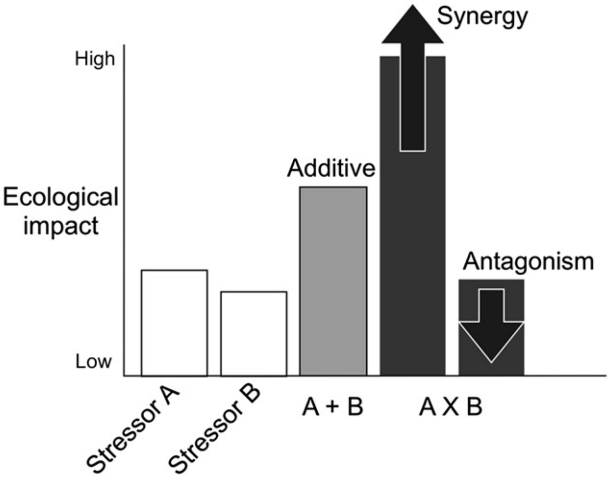

Figure 1 The cumulative ecological impact of two stressors can result in simple additive effects, synergies, or antagonisms. Synergies and antagonisms are examples of 'ecological surprises,' where the combined impact of two or more stressors is greater than (synergy) or less than (antagonism) the simple additive sum of the two individual stressors.

The loss of healthy reefs may therefore limit the protection they can provide to coastal communities (Barbier et al. 2011). Declining coral reef fish and invertebrate populations stemming from declines in the quality or availability of reef habitat will have economic consequences for coral reef fisheries, and the millions of people in developing countries that depend on coral reef resources for subsistence and livelihoods (Pratchett et al. 2008; Barbier et al. 2011). There are therefore very convincing ecological and economic reasons to understand how multiple stressors interact to produce such drastic effects, and whether there might be ways to manage stressors to mitigate these interactions.

There is increasing concern that the decline of coral reefs (and other ecosystems impacted by multiple stressors) has been driven by synergies, nonadditive interactions between two or more stressors characterized by a combined impact that is greater than the simple sum of the individual impacts (Folt et al. 1999; Breitburg and Riedel 2005) (Figure 1). In effect, synergies occur when the impact of two or more stressors is greater than the sum of the parts. Synergies are one type of unpredictable 'ecological surprise' that can accelerate biodiversity loss (Brook et al. 2008) and impair the functioning of marine ecosystems (Paine et al. 1998; Hoegh-Guldberg and Bruno 2010). However, the presence of multiple stressors does not necessarily imply that synergies should be expected. For example, the impacts of multiple stressors can be mitigated by antagonisms, which are interactions where the combined impact is less than the sum of the individual impacts (Figure 1). The combined impact of multiple stressors can also be simply equal to the sum of the impacts of individual stressors, resulting in a straightforward additive effect (Folt et al. 1999; Breitburg and Riedel 2005) (Figure 1). Two recent meta-analyses of hundreds of published studies, evaluated the combined impacts of multiple stressors in terrestrial and aquatic ecosystems, suggest that synergies, antagonisms, and additive effects may be equally common when two stressors are acting (Darling and Côté 2008; Crain et al. 2008). However, the addition of a third stressor can often, though still not always, result in a synergistic outcome (Crain et al. 2008).

Evaluating the cumulative impacts of multiple stressors is critical to forecast future ecological change on coral reefs and effectively manage the combined impacts of multiple stressors. One of the greatest scientific uncertainties concerning the decline of coral reefs is how local human impacts (i.e., fishing, pollution) will interact with global climate change (Knowlton and Jackson 2008). It is generally assumed that local human impacts will erode the ability of coral reefs to resist the impacts of climate change and that coral reefs already exposed to human disturbances will be less resilient to climate change, and could 'tip' into a degraded and less desirable coral-poor state sooner than more pristine reefs. Thus, enhancing resilience by reducing the impacts of local stressors is deemed by many to be crucial for conserving coral reefs in the face of global climate change.

4.21.3 What Is Resilience?

The concept of resilience now underpins much of the thinking about the management of coral reefs. It was first proposed by Holling (1973), who defined resilience as "a measure of the persistence of systems and of their ability to absorb change and disturbance, and still maintain the same relationships between populations or state variables." Holling explicitly recognized that ecosystems are dynamic, spatially and temporally heterogeneous, and can exist in multiple alternative states depending on environmental conditions. For example, temperate lakes in North America and Europe can persist in a state of clear water or in an alternative state of high turbidity depending on the input of nutrients and the presence of predatory fishes. Similarly, savannas and grasslands may either be grass-dominated or shrub-dominated, depending on the intensity of grazing (Folke et al. 2004). Coral reefs are no different. Under certain conditions, coral reefs are 'coral-rich,' with a high cover of coral and a low cover of macroalgae, but in altered environments they can transform, sometimes quickly, into coral-poor reefs with extensive stands of fleshy algae (Bellwood et al. 2004). Other alternative states are also possible for coral reefs, such as assemblages dominated by sponges and/or soft corals (Norström et al. 2009). Resilience may therefore be functionally defined as the capacity of an ecosystem to absorb and adapt to shocks and disturbances without fundamentally shifting into an alternative state (Scheffer et al. 2001; Hughes et al. 2010).

An ecosystem may be resilient for two reasons. On the one hand, an ecosystem may be resistant to a given perturbation. Carpenter et al. (2001) defined resistance as the amount of external pressure needed to bring about a given amount of disturbance in a system. For example, through differing species compositions, with some assemblages made up of species that can withstand greater magnitudes of the perturbation of interest than other assemblages. On the other hand, two ecosystems may have similar resistance to a given perturbation, but may differ in their potential for recovery, that is their ability and/or swiftness to return to a state that is functionally similar to the pre-disturbance state. Functional similarity is the operative term here. Recovery does not mean returning to a state identical to the original one, but to a state that responds to the same drivers and feedbacks. Resistance and recovery are therefore two sides of the resilience coin, and it is not clear how they covary, if at all.

The dual nature of resilience, developed in the general ecological literature, has for some reason not always been fully embraced by coral reef scientists. In the coral reef world, the term resilience has become interchangeable with recovery. For example, Hoegh-Guldberg et al. (2007) defined resilience as "the rate at which an ecosystem returns to a particular state after a perturbation or disturbance." Similarly, Hughes et al. (2007) equate resilience with "the ability of coral reefs to absorb recurrent disturbances and rebuild coral-dominated systems." Several authors have recognized the importance of both resistance and recovery, but called the latter 'resilience' (West and Salm 2003; Knowlton and Jackson 2008). Here, we use the terminology that resilience is a two-part process of 'resistance,' the ability of a system to withstand disturbance, and 'recovery,' the capacity of a system to bounce back to the original, pre-disturbance state.

Two important general issues surrounding resilience remain. The first is that resilience is not always a good thing. Resilience can be desirable or undesirable (Carpenter et al. 2001), depending on whether it characterizes ecosystem states that are or are not favored by society. Some ecosystem states, such as grasslands converted to desert because of overgrazing, are undesirable because they provide reduced services, but they can be highly resilient to external shocks. The second, related to the first, is that resilience needs to be defined not only in terms of the ecosystem state (i.e., resilience of grassland or of desert; resilience of coral-rich reefs versus coral-poor reefs) but also in terms of the perturbation of interest. A particular ecosystem state may be highly resilient to one type of disturbance, but less so to another. In this chapter, we specifically consider the resilience of coral-rich reefs to climate change-induced coral bleaching.

4.21.4 The Conventional View of Coral Reef Resilience

For most coral reef scientists, the conventional view of resilience is that pristine, unstressed coral communities are highly resilient to climate change and coral bleaching, and that human impacts reduce the ability of coral reefs to withstand such impacts (Hughes et al. 2003; Hoegh-Guldberg et al. 2007; Hughes et al. 2010). This conventional view of cumulative impacts and resilience on coral reefs is illustrated in the simple conceptual model shown in Figure 2(a), which shows the relationship between ecosystem state and climate disturbance. Ecosystem state can be thought of in terms of coral cover or coral species diversity, with the implicit notion that a coral-rich state is more desirable, while climate disturbance can incorporate both changes in mean and increased variability of various climate metrics, such as temperature. The general trajectory of coral reef ecosystems under thermal stress is expected to be sigmoidal (Figure 2), with relatively little change in ecosystem state over low levels of climate disturbance, and a precipitous shift to an alternative state once a climate threshold, commonly referred to as the tipping point, is exceeded (Hughes et al. 2010). The magnitude of the threshold can be used as a proxy for the resistance aspect of resilience.

This model can easily be adapted to reflect the additional impact of non-climatic, local stressors on coral reef state, and how this modifies the response of coral reefs to climate disturbances. According to the conventional view of resilience, more pristine coral reefs (i.e., with a higher coral cover and species diversity) have a high resistance to climate change and will only cross the tipping point and shift into an alternative ecosystem state at high levels of climate disturbance (Figure 2(a)). However, as non-climatic, local impacts such as fishing or pollution degrade the original ecosystem and move the state of the ecosystem down the y-axis, the coral community moves from a pristine to a disturbed, and finally a very disturbed assemblage (see photos, Figure 2). In response, the tipping point shifts to the left, whereby already disturbed ecosystem are less resistant to climate disturbances.

The mechanisms underscoring the conventional view of resilience often implicate overfishing and nutrient pollution in the loss of coral resilience (or really, resistance) to thermal stress and subsequent bleaching (Bellwood et al. 2004; Knowlton and Jackson 2008). Overfishing of herbivorous grazing reef fishes and nutrient pollution from coastal runoff can lead to the proliferation of macroalgae, which can harbor harmful microbes and pathogens that can increase coral disease (Nugues et al. 2004; Dinsdale et al. 2008). Fishing can also damage and break corals (Mangi and Roberts 2006) and reduce the types of suitable coralline algae substrate available for the settlement and growth of juvenile corals (O'Leary et al. 2012). Impacted colonies have to spend energy on tissue and skeleton repair, which can limit their ability to withstand and recover from climate-related stresses, such as coral bleaching and ocean acidification (Knowlton and Jackson 2008; Anthony et al. 2009, 2011; Carilli et al. 2009).

If coral reef state varies in relation to climate disturbance as depicted in Figure 2(a), then two predictions arise. First, coral communities exposed to local or chronic disturbance should be more susceptible to coral bleaching following thermal stress than less degraded, 'pristine' communities. Second, the combined impacts of local disturbances and global climate change should be either additive or synergistic, but definitely not antagonistic. We now briefly evaluate the empirical evidence for each prediction.

4.21.4.1 Prediction 1: Are Disturbed Coral Reefs More Susceptible to Climate Change?

The conventional view of resilience assumes that disturbed coral communities are less resistant to climate change than more 'pristine' and undisturbed coral communities. The observation that thermally induced coral bleaching events are increasing in frequency and extent (McWilliams et al. 2005; Hoegh-Guldberg et al. 2007) on reefs that are globally degraded (Gardner et al. 2003; Bruno and Selig 2007) could be taken as supporting evidence for the assumption that degraded reefs are more susceptible to climate change. However, this

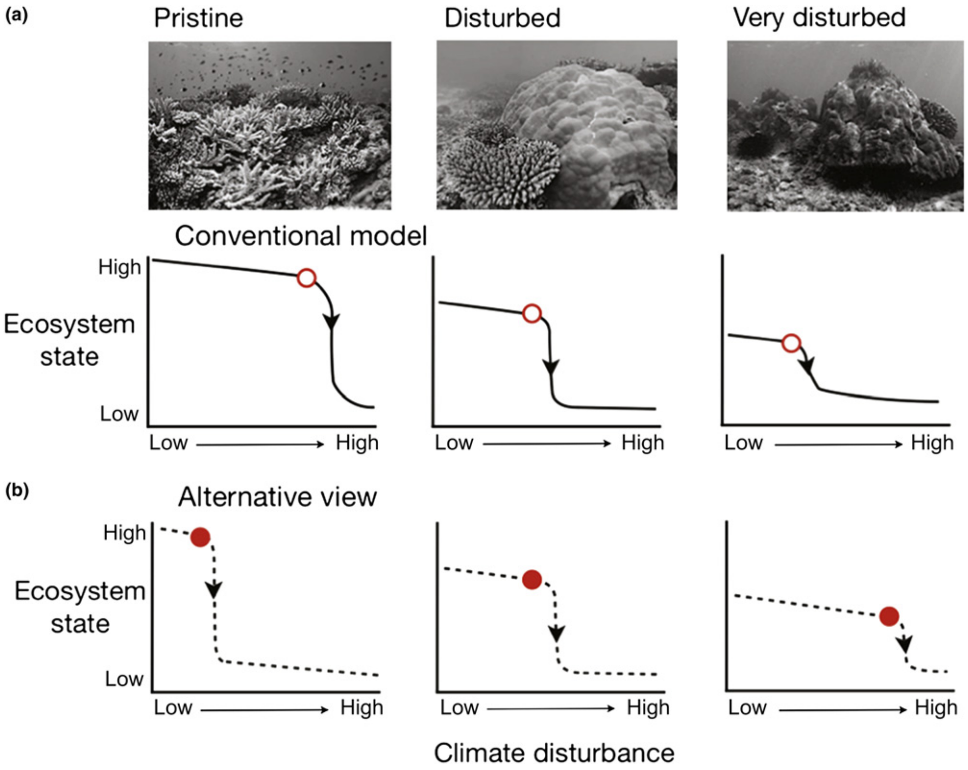

Figure 2 The relationship between ecosystem state and climate disturbance under conventional and alternative views of resilience. With the conventional view of resilience (a; solid lines), pristine, coral-rich reefs (left panel) are expected to tip into an alternative coral-poor state only at very high levels of climate disturbance. As coral reefs are increasingly degraded by chronic anthropogenic impacts (i.e., fishing, pollution; middle and right panels), the tipping points (open circles) are expected to shift to the left such that disturbed reefs are less resistant to climate disturbance than pristine reefs. In an alternative view of resilience (b; dashed lines), pristine coral reefs (left panel) are dominated by sensitive species, which have a limited resistance to climate disturbances, such as coral bleaching, which allows these reefs to tip very easily into an alternative coral-poor state. As human impacts remove these sensitive species from reefs (middle and left panels), the tipping points (solid circles) shift to the right, such that disturbed reefs may be more resistant to climate change. Photographs by Emily Darling.

signal is confounded by increasing sea surface temperature anomalies over time (Hoegh-Guldberg et al. 2007; Hoegh-Guldberg and Bruno 2010). Thus, even in the absence of degradation caused by local stressors, more widespread and/or intense bleaching would be expected if the response of corals is directly related to temperature.

There are arguably no pristine coral reefs left in the world. However, reefs around remote, uninhabited islands, such as the northern Line Islands in the Central Pacific, may be as close to pristine as any reefs on Earth (Knowlton and Jackson 2008). These reefs boast extraordinary densities of sharks and other large predatory fishes and high coral abundance (Sandin et al. 2008), which reflect the lack of local anthropogenic pressures which are pervasive elsewhere. These reefs should be highly resistant to high-temperature events. Yet, the corals of Palmyra, the best studied of the northern Line Islands, can bleach as severely as more impacted reefs (i.e., in American Samoa, Fiji, and the Philippines), despite the fact that they experience similar temperature regimes (Oliver and Palumbi 2009). We agree with Knowlton and Jackson (2008) who state “there are no data to suggest that corals become less vulnerable to bleaching with reduced local impacts.”

4.21.4.2 Prediction 2: Do Multiple Stressors Interact Additively or Synergistically on Coral Reefs?

The second assumption of the conventional view of resilience is that global climate change could reinforce the negative impacts of existing local stressors through additive or synergistic interactions. There have been few empirical studies of how multiple stressors interact on coral reefs. Until recently, most were small-scale experiments carried out in the laboratory, that involved only two stressors, and did not use the appropriate statistical techniques to reveal the interaction type unambiguously (Dunne 2010).

In one of the few attempts at unraveling the nature of interactions between local and climate stressors on natural reefs, Darling et al. (2010) evaluated the interaction between fishing and coral bleaching on coral cover using a long-term time series on Kenyan coral reefs. Not surprisingly, they found that both stressors influenced coral cover. A comparison of fished and unfished reefs, prior to the 1998 mass bleaching event, revealed that fishing on its own reduced coral cover by 51%, while a comparison of unfished reefs before and after the mass bleaching event suggested that the effect of bleaching was much larger, reducing coral cover by 74%. However, on reefs

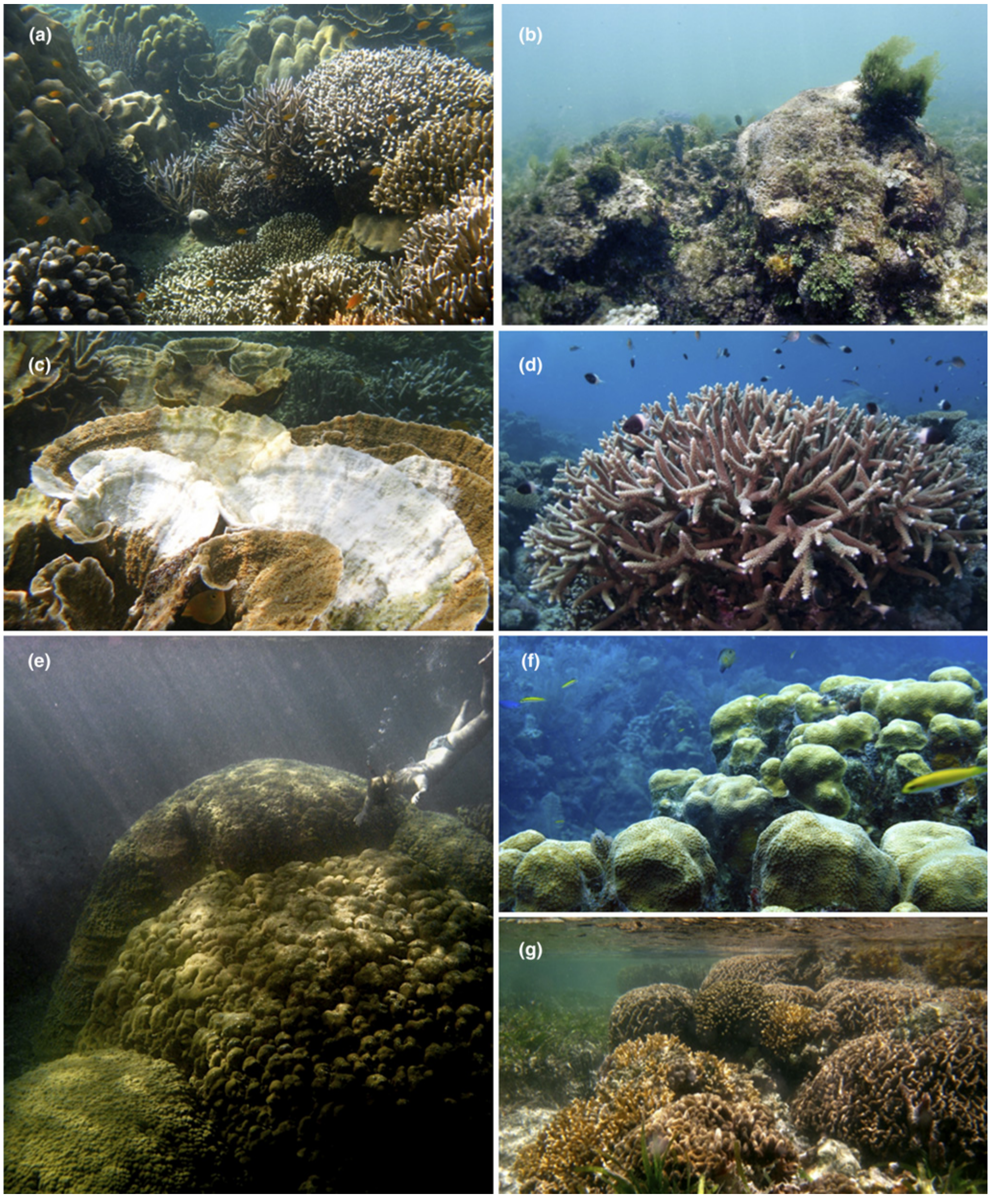

Figure 3 Examples of coral species with different responses to human disturbances and climate change. The type of coral community can determine whether a coral reef shifts from a coral-rich state (a) into a coral-poor state (b), immediately following climate disturbances, in particular coral bleaching. Stress-sensitive corals, such as species of plating *Montipora* (c) and branching *Acropora* (d), often occur on pristine and less disturbed coral-rich reefs, but are highly sensitive to thermal stress and coral bleaching. Large, slow-growing corals, such as species of *Montastraea* (e) and massive *Porites* (f), as well as small, fast-growing opportunistic and 'weedy' corals (g: Stylophora hystrix and branching Porites species) are often tolerant to human disturbances and also less affected over the long-term following bleaching. Photographs by Emily Darling.

subjected to both stressors (i.e., postbleaching, fished reefs), coral cover had declined by 72% on average, which was consistent with an antagonistic interaction, or a very weakly additive effect. This is not what the conventional view of coral reef resilience would have predicted.

4.21.5 An Alternative View of Resilience in a Disturbed World

There is an alternative view of ecological resilience to multiple stressors, which suggests that degraded reefs may, in fact, be more rather than less resistant to climate disturbances (Côté and Darling 2010). This alternative outlook is predicated on the fact that disturbance-sensitive taxa are lost following the impacts of local stressors, which can explain why more intact reef communities do not appear to be more resilient to climate disturbance. Local stressors can actually increase the relative abundance of disturbance-tolerant species within a community (Rachello-Dolmen and Cleary 2007; McClanahan et al. 2007a, 2007b; Cleary et al. 2008), and thus, the ability of an ecosystem to resist the impacts of climate disturbance.

Species are not lost randomly following disturbances (Srivastava and Vellend 2005; Ives and Carpenter 2007; Bracken et al. 2008; Zavaleta et al. 2009). Instead, disturbed ecological communities tend to first lose species with stress-sensitive life histories. Community composition shifts as these stress-sensitive species are replaced with stress-tolerant and opportunistic species that rapidly colonize following a disturbance. Thus, the remaining community can be composed of 'survivor' stress-tolerant and weedy species, which can be expected to be as resistant, or even more resistant, to subsequent climate disturbances.

There is ample evidence that such community shifts are occurring on coral reefs (**Figure 3**). Changes in the structure and composition of coral communities have been observed in the aftermath of diverse natural and anthropogenic disturbances, such as hurricanes and storms (Hughes and Connell 1999; Bak et al. 2005; Madin et al. 2008), pollution (Rachello-Dolmen and Cleary 2007), sedimentation (McClanahan and Obura 1997; Aronson et al. 2004; Dikou and van Woesik 2006; Cleary et al. 2008; Jupiter et al. 2008), fishing (McClanahan 2008; Darling et al. 2010), disease (Aronson et al. 2004), and outbreaks of coral predators (i.e., crown-of-thorns sea stars, Pratchett et al. 2009). In the Indo-Pacific region, the immediate effects of disturbances can generally shift coral communities from assemblages of stress-sensitive branching and plating corals, such as species of *Acropora* and *Montipora*, toward altered assemblages of stress-tolerant massive corals such as species of massive *Porites*, and faviids, such as species of *Cyphastrea and Favia* (Loya et al. 2001; McClanahan et al. 2007a, 2007b; Rachello-Dolmen and Cleary 2007; Cleary et al. 2008). In the Caribbean, the primary reef-building corals *Acropora* and *Montastrea* species have been replaced by 'weedy' coral species that form small colonies, grow quickly, and are short-lived (Knowlton 2001; Precht and Miller 2006). For example, the relative abundance of 'weedy' *Porites astreoides* has increased significantly over the past four decades (Green et al. 2008) as coral cover has declined – a sign of reef degradation – across the region (Gardner et al. 2003). Disturbed Caribbean reefs have also been shown to converge to communities dominated by *Agaricia*, whose opportunistic life history and high environmental tolerance have been suggested to explain its persistence on degraded reef habitats (Aronson et al. 2004).

The shift from stress-sensitive to stress-tolerant corals may make communities on disturbed reefs actually more resistant to bleaching and climate change. This alternative view of reef resilience is depicted in **Figure 2(b)**. Pristine or undisturbed communities are often dominated by disturbance-sensitive species that have limited resistance to climate stress and can tip into an alternative state at low levels of climate disturbance. When pristine reefs are exposed to the impacts of local stressors, their coral communities are altered toward a higher relative abundance of disturbance-tolerant species. Thus, degradation can shift the tipping point in response to climate change to the right, resulting in disturbed ecosystems having a higher resistance to climate disturbance than pristine, unstressed reefs. This alternative view of resilience will depend on whether a species' tolerance to a non-climatic disturbance is correlated with its tolerance to climatic impacts (i.e., positive cotolerance, Vinebrooke et al. 2004). Currently, there has been no evaluation of cotolerance in corals, although the patterns of species replacement within coral communities described above provide anecdotal evidence that cotolerance exists and that it may generally be positive (Côté and Darling 2010).

The resistance of coral communities to climate change will likely be a dynamic process as coral species adapt and acclimatize to thermal stress. Such adaptation can occur if corals acquire heat-tolerant symbiotic zooxanthellae (Berkelmans and Van Oppen 2006) or through the adaptation of host coral populations. For example, coral communities in South East Asia that bleached severely during the 1998 mass bleaching event were less impacted by a second bleaching event in 2010; both bleaching events were triggered by comparable temperature anomalies (Guest et al. 2012). What is remarkable is that some bleaching-sensitive corals, such as species of *Acropora* and *Pocillopora*, displayed more resistance to the successive bleaching event in 2010, possibly because of adaptation through natural selection – the loss of bleaching-susceptible individuals from the population in 1998 resulted in the survival and reproduction of bleaching-tolerant individuals that then increased the mean bleaching tolerance within the population in 2012 (Guest et al. 2012). It is unclear how generalizable these results are to other reefs and other coral species. Nonetheless, it provides some hope that even some of the most vulnerable corals would be able to increase their resistance to future thermal stress and coral bleaching events.

The alternative view of resilience focuses on some of the earliest changes in coral communities, the replacement of stress-sensitive corals with stress-tolerant and weedy corals. Such initial changes in ecological communities may increase the resistance of coral communities to climate change. However, species losses and declines, and patterns of community disassembly are not a single event, but a series of successive events that can reflect progressive and cascading losses in community and ecosystem function (Zavaleta et al. 2009). Even thermally tolerant species will have limits, which may be exceeded by future ocean warming and acidification (Hoegh-Guldberg et al. 2007). Overwhelming anthropogenic stressors may also precipitate the loss of even these hardy coral species and cause the replacement of coral communities with macroalgae, soft corals, seagrasses, and/or sponges (Norström et al. 2009). Furthermore, disturbed coral communities and alternative noncoral systems may be unable to support the immense biodiversity and economic benefits provided by intact coral reef ecosystems. A critical goal for coral reef conservation is therefore preserving coral populations and the reef architecture that supports reef-associated organisms and services, but how to do this will depend on how resilience to the cumulative impacts of local stressors and climate change actually works.

4.21.6 Implications for Conservation and Management

Increasing the resilience of coral reefs to climate change is a critical challenge for conservation and management. Local stressors are expected to erode the ability of coral reefs to withstand variations and longer-term change in climate conditions, particularly rising SSTs that provoke coral bleaching (Hughes et al. 2003, 2010; Knowlton and Jackson 2008). It is perhaps not surprising then that removing local stressors to increase resilience to climate change has emerged as a strong focus of coral reef management, perhaps more so than for any other ecosystem.

The conventional view of resilience suggests that removing local stressors and reducing human impacts should increase the ability of coral reefs to withstand climate change. As ecosystems are degraded by anthropogenic stressors, from pristine to disturbed, to very disturbed states, management that seeks to control local stressors and reverse degradation is therefore expected to increase resistance by shifting the tipping point back to the right and keeping reefs further away from such thresholds (**Figure 2(a)**).

One of the most popular ways that has been suggested to increase resilience to climate change is through the use of marine reserves, or MPAs (Hughes et al. 2003, 2010; Bellwood et al. 2004; Mora et al. 2006; Hoegh-Guldberg et al. 2007). MPAs are a form of spatial management that seek to control local stressors, primarily fishing. Integrated land and sea conservation efforts that target terrestrial activities adjacent to MPAs may also reduce coastal runoff and the amount of nutrient and sediment pollution that reaches coral reefs, but these are still relatively uncommon.

MPAs have been shown to have positive effects on the abundance and diversity of a variety of fish and invertebrates within their boundaries (Halpern 2003). Many reserves, but not all, have increased coral cover (McClanahan 2008; Selig and Bruno 2010; Darling et al. 2010), coral species diversity (McClanahan 2008), and coral recruitment (Mumby et al. 2007), with concomitant declines in macroalgal cover (Mumby et al. 2007; Mumby and Harborne 2010). Such benefits provided to coral communities are an indirect result of protecting fish populations from fisheries. In particular, the protection and recovery of populations of herbivorous fishes (i.e., parrotfishes and surgeonfishes) can maintain a variety of critical ecosystem functions, such as bioerosion, which exposes the reef matrix for coralline algae and juvenile corals, scraping, and grazing, which removes algae, leading to higher coral cover and coral recruitment (Elmqvist et al. 2003, Bellwood et al. 2004; Mumby et al. 2007). Healthy populations of herbivorous reef fishes can reinforce positive feedbacks that promote coral recruitment and healthy coral cover within MPAs, while the loss of herbivores can keep reefs in a coral-poor and unhealthy state (Mumby and Steneck 2008). Higher species and functional diversity on protected reefs can provide ecological insurance and functional redundancy, both of which are expected to increase resilience to climate disturbances, such as coral bleaching events (Loreau et al. 2003; Nyström et al. 2008).

However, any positive effects of MPAs on the resilience of corals to climate change may be unintentional. MPAs were designed to target local-scale impacts of anthropogenic stressors not the global-scale impacts of climate change (Hughes et al. 2010). There is no evidence that marine reserves are located in areas that are at less risk for thermal stress and coral bleaching (Maina et al. 2008), nor is there any expectation that marine reserves could alleviate the impacts of ocean acidification on corals (Mumby and Steneck 2008). Thus, it is probably not surprising that marine reserves do not reduce the frequency or intensity of thermally induced coral bleaching (Hughes et al. 2003; Coelho and Manfrino 2007; Mumby and Steneck 2008), or bleaching-induced coral mortality (Graham et al. 2008; Darling et al. 2010; Selig et al. 2012). It is sobering that the impacts of extreme events (i.e., anomalously high SSTs) can, in a single bleaching event, override years of coral recovery within MPAs (Darling et al. 2010; Selig and Bruno 2010).

Why are corals within MPAs not protected from coral bleaching? Why do they in fact often experience greater mortality following bleaching than corals on unprotected reefs (Graham et al. 2008; Darling et al. 2010)? The vulnerability of protected corals to thermal stress and bleaching could reflect the higher initial coral cover within MPAs; when disturbance strikes, there is simply more coral to lose (Graham et al. 2008, 2011a, 2011b). However, this is unlikely to be the whole story. The types of corals fostered by MPAs are often very sensitive to disturbance, and thus, it may not be only about how much coral can be lost, but how easily it can be lost (Darling et al. 2010). Notably, there is often a higher abundance of thermally sensitive corals, such as species of *Acropora* and *Montipora*, within marine reserves, leading to increased susceptibility of protected coral assemblages to climate disturbances (McClanahan et al. 2007a, 2007b; Darling et al. 2010). These differences in the types of corals and coral assemblages between protected and unprotected reefs could be due to an initial bias in site selection, whereby less degraded coral reefs with higher diversity of coral species are favored as sites where MPAs are established (Darling et al. 2010; Selig and Bruno 2010). There are few old and effectively enforced MPAs with pre-protection baseline data to evaluate the potential effects of site bias. However, in Kenya where data do exist for one MPA prior to protection, Darling et al. (2010) found that there was no difference in coral cover between the incipient MPA and fished reefs surveyed in the same year, suggesting that the effects of protection on resilience, at least in some MPAs, can be independent of bias associated with habitat selection. At such sites, protection itself, by eliminating destructive fishing and restoring fish populations, may favor the ecological succession of competitively dominant branching and plating corals that may be extremely sensitive to thermal stress and bleaching mortality.

The observation that coral assemblages within MPAs are disproportionately vulnerable to coral bleaching and climate change is consistent with the alternative view of resilience, which holds that managing local stressors in order to return ecosystems to a more pristine state may actually increase their vulnerability to climate disturbances. Thus, the effect of management action that seeks to control local anthropogenic disturbances and move communities back from a disturbed to a pristine state may inadvertently shift the tipping point back to the left by recovering pristine assemblages of disturbance-sensitive species (**Figure 2(b)**). The ultimate result may be to compromise the resistance of protected reefs to climate disturbances.

The cynical interpretation of the alternative view of resilience is that if degraded reefs are likely to weather the impacts of climate change, then we should allow degradation by local stressors to proceed. This would be extremely short sighted and the alternative view of resilience certainly does not advocate against the value of MPAs. MPAs provide diverse and unparalleled benefits to biodiversity and ecosystem function on coral reefs. The alternative view of resilience is instead a call to action for local management actions that are climate-smart.

4.21.6.1 Three Ways to Manage Coral Reefs in the Face of Climate Change

What are the options for managing coral reefs in the face of climate change if the alternative view of resilience applies? In other words, how can management increase the resistance of coral reefs to climate change if the conventional approach of controlling local stressors is not effective? One explanation for why MPAs have not buffered coral reefs from climate change disturbances, such as mass coral bleaching, is because of the current way they are designed (Selig et al. 2012). We can suggest three strategic ways that might help management to mitigate the risk from ocean warming and subsequent bleaching on coral reefs.

First, the placement of MPAs should be strategic with respect to where the greatest threat of future warming and thermal stress exists. The location of MPAs is too often the result of socio-political compromises and too seldom based on scientific advice. Spatial planning must take into account the fact that warming climate varies heterogeneously across the seascape. Not all areas of the world's oceans are warming equally, nor are they expected to in the future (i.e., Maina et al. 2011) and yet few MPAs are designed to take advantage of naturally cool conditions that can avoid the worst impacts of coral bleaching. For example, only 2 out of 61 managed coral reefs in the Western Indian Ocean are located in areas of low climate susceptibility (Maina et al. 2008). Finding and predicting 'cold spots' where MPAs will experience less thermal stress is critical for the survival of coral biodiversity. Some areas, such as the northwest Caribbean, and northern Madagascar and southern Tanzania in the western Indian Ocean appear to be exposed to low levels of climate stress (McClanahan et al. 2007a, 2007b; Maina et al. 2011). It is therefore imperative to target these climate 'cold spots' for protection (West and Salm 2003; Mumby and Steneck 2008). This will be difficult because it means that MPAs planning at the national scale may no longer be relevant. Instead, regional, transboundary coordination will be needed to identify priority areas and effectively protect them. Moreover, countries near 'cold spots' may have to bear the opportunity costs associated with MPAs establishment, such as the loss of fishing grounds, to generate conservation benefits at the regional scale. These inequalities may call for a reassessment in the way MPAs are funded in order to shift the financial burden from national to regional pockets (i.e., Balmford et al. 2004).

Second, MPA design must become adaptive. By this, we mean that the size, shape, and location of MPAs can be changed in response to new information. Flexible boundaries would allow MPAs to track the changing regimes and impacts of thermal stress and climate change (Maina et al. 2011). Corals have one of the fastest rates of poleward range expansion in response to climate change and range shifts have been observed to be as fast as 14 km year^{-1} (Yamano et al. 2011). Moving-target MPAs could therefore be used to protect novel coral assemblages, as their range limits expand or contract with climate change (Hobday 2011). MPA networks may also facilitate the maintenance of connectivity even with the impacts of climate change (Mumby et al. 2010; McLeod et al. 2009). It is widely held that MPAs work best when embedded in a web of protected areas, which are interconnected to various degrees by the exchange of nutrients, eggs, juvenile, and adult organisms that disperse with currents or actively migrate (WCPA/IUCN 2007). Patterns of connectivity are very likely to be affected by the regional and local impacts of climate change, which can alter currents and accelerate temperature-dependent processes such as larval development (O'Connor et al. 2007). However, actually implementing climate-tracking MPAs would require a major overhaul of the legislative process leading to MPAs designation, which in most places moves at glacial speeds.

Third, bigger may be better when it comes to MPAs. There is strong enthusiasm for the establishment of 'mega-MPAs' (i.e., Knowlton and Jackson 2008; Sheppard et al. 2012). Some recently established MPAs in the Pacific and Indian Oceans are very large indeed. The Chagos Archipelago, for example, is the world's largest MPA and covers more than 550 000 km^2, which is larger than France or the state of California (Sheppard et al. 2012). Large MPAs can provide important baselines for what nearly intact coral reef systems look like and how they function (Knowlton and Jackson 2008). However, it is unclear whether such 'pristine' baselines will be informative for understanding the dynamics of degraded reefs or if it is even possible to return severely degraded reefs to a state approaching these gold standards. Nevertheless, the main advantage of very large MPAs in terms of bolstering resistance to climate change is that not all reefs within them may be affected by acute climatic disturbances. Owing to their sheer size, mega-MPAs may well encompass climatic 'cold spots' provided by upwelling and other local oceanographic conditions (i.e., West and Salm 2003). Also, given the average size of most thermal anomalies, it is more likely that some areas within very large MPAs would escape thermal stress and bleaching anomalies (Selig et al. 2012). If large MPAs can provide a bleaching refuge to coral populations, this may give corals a chance to adapt through the natural selection of thermally tolerant symbionts and coral hosts (Berkelmans and Van Oppen 2006; Guest et al. 2012). Finally, large MPAs will also hold, in absolute terms, larger populations of stress-resistant corals than smaller MPAs.

4.21.6.2 Managing for Resistance versus Recovery

Even if protection does not usually enhance reef resistance to climate change, protection may provide substantial benefits for other facet of resilience: recovery. Many ecosystems have the capacity to recover from catastrophic disturbances. Large and infrequent pulse disturbances are the 'usual state of affairs' and in the past, they did not override the eventual recovery of ecosystems (Paine et al. 1998). For example, historical cyclones occur every decade or so on reef crests of the Great Barrier Reef and are considered 'normal' events that, until recently, did not provoke shifts to an alternative and undesirable macroalgal-dominated state (Hughes et al. 2010). This is likely because historical reefs were in a more pristine condition and able to bounce back following even large-scale natural disturbances. However, there is grave concern (and some empirical evidence) that the increasing scale of anthropogenic stressors is limiting the ability of ecosystems to recover from natural cycles of disturbance. For example, coral reefs along the Mesoamerican Barrier Reef in Belize and Honduras that had experienced more anthropogenic stress recovered more slowly, in terms of coral growth rates, from the 1998 bleaching event than less impacted reefs (Carilli et al.

2009). Similarly, the pristine and isolated reefs of Kingman and Palmyra in the Line Islands had higher rates of recovery following warm water and coral bleaching events than the more disturbed coral reefs of nearby Kiritimati and Tabuaeran, which are inhabited by people (Sandin et al. 2008).

MPAs are expected to increase coral recovery by maintaining the diversity of reef fish species and functional groups, particularly herbivorous fishes that graze algae and facilitate the recruitment of juveniles corals (Bellwood et al. 2004; Mumby et al. 2007; Hughes et al. 2010). The evidence for coral recovery following bleaching events within MPAs is still equivocal, but hopeful. Studies of reefs in the Bahamas (Mumby and Harborne 2010) and Indian Ocean (Ateweberhan et al. 2011) have found greater rates of recovery of live coral cover within MPAs than on unprotected reefs. However, studies of MPAs from around the world (Selig and Bruno 2010) and MPAs within Kenya (McClanahan 2008; Darling et al. 2010), and the western Indian Ocean (Graham et al. 2008) have found no evidence of higher recovery rates of coral cover within MPAs, and in some cases, coral recovery can be significantly slower in MPAs than on unprotected reefs (Graham et al. 2011a, 2011b). MPAs, especially older ones, can nevertheless be effective at preventing further coral losses that are occurring on more disturbed reefs, although any benefit of this protection can be wiped out following bleaching (Selig and Bruno 2010, Selig et al. 2012). Overall, the effects of MPAs on coral recovery are strongly context-dependent and differ across regions, the type of disturbance and the amount of postdisturbance coral cover (Graham et al. 2011a, 2011b). The species composition of the remaining coral community can also affect recovery as fast-growing, opportunistic genotypes or species will recover more quickly than slower-growing corals (Selig and Bruno 2010). It would be interesting in this context to see whether the fast-growing taxa that promote reef recovery are robust or sensitive to climate disturbances.

When considering the increasingly stressful future for most ecosystems, it is imperative to clearly understand the cumulative impacts of multiple stressors, as well define and distinguish between the two processes of resilience: ‘resistance’ and ‘recovery.’ While the main focus of management has been on recovery, finding ways to bolster resistance may be as important, if not more important, in the years ahead. For example, future projections of climate change predict that bleaching-inducing thermal anomalies will become more frequent (Hoegh-Guldberg et al. 2007; Donner 2009), which, if correct, would shrink the available window of coral recovery in between bleaching events. Perhaps this window is already too small, as many coral reefs have failed to recover even after more than a decade following the 1998 worldwide mass coral bleaching event (Graham et al. 2011a, 2011b). Furthermore, it is unclear if there will be any potential for recovery to chronic climate stressors, such as increasing average SSTs and the rising acidity of the world’s oceans.

Conclusions

The cumulative impacts of climate change and local human impacts of overfishing and pollution threaten the diversity, ecological function, and ecosystem services provided by coral reefs to millions of people around the world. Such ongoing and unprecedented changes, particularly the two faces of climate change – ocean warming and acidification – are creating a ‘brave new ocean’ with wide-reaching ecological consequences (Jackson 2008). Finding workable solutions is not easy and it is important to remember that any successful conservation initiative will require the support of local communities. The best opportunities for success may be to try many different tactics of conservation and management in order to hedge our bets as we identify a portfolio of actions that will have the most success at maintaining the ecological and socioeconomic services of marine ecosystems.

Strategic local conservation and management actions will hopefully buy us some time for globally supported initiatives to limit the human drivers of climate change. MPAs, and other forms of local land and sea management, are important tools to manage coral reefs, but they will need to be climate-ready and climate-smart. Coral reefs have a fighting chance if MPAs can protect large areas of critical habitat and are placed in areas of the ocean that are more likely to escape the full force of climate change. Identifying climate-resistant species and locations that are able to survive climate change will be equally important, as we expand our focus of resilience-based management to include both resistance and recovery. However, local conservation and management actions will likely never be the silver bullet that can single-handedly protect ecosystems against the risk from current and future climate conditions, particularly the unparalleled threat of ocean acidification.

The continuing degradation of coral reefs from climate change and other human impacts is an invaluable warning for other ecosystems around the world. Coral reefs are likely to be one of the first ecosystems to reach a tipping point of cumulative impacts. Understanding, quantifying and managing for multiple stressors on coral reefs can provide a benchmark for other ecosystems. Ecosystem-based management actions and policies that explicitly consider, evaluate, and adapt for interactions between stressors are immediately needed. We believe there is hope for the future of coral reef ecosystems and the millions of people who depend on the resources provided by coral reefs every day. However, in addition to managing local impacts, it is critical that we tackle the root anthropogenic causes of climate change in order to guarantee that future generations can benefit from the “surpassing beauty … and wonders of a coral sea” (Wallace 1869).

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4.22 Vulnerability of Estuaries to Climate Change

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Glossary

Autotrophic organisms Photosynthesize (or chemosynthesize) to produce organic carbon, releasing oxygen; in an autotrophic estuary, oxygen production from photosynthesis and chemosynthesis exceeds consumption by respiration.

Barrage Is an artificial obstruction in a river designed to increase its depth or to divert its flow.

Benthic organisms (*benthos*) Live on or in the bottom sediments.

Diadromous fish Have some life stages in freshwater and some in saltwater. This includes *anadromous* species such as salmon which spawn in freshwater but spend much of their lives in saltwater, and *catadromous* species such as blue crabs that spawn in estuaries and rear in the ocean.

Epibenthic organisms Live on or near the bottom but may move up into the overlying water.

Epiphytic organisms Are algae and other small organisms that live on plant stems and leaves.

Eutrophication An increase in the rate of organic matter supply to an ecosystem, often to the point of undesirable consequences such as hypoxia.

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Heterotrophic organisms Oxidize organic matter to obtain energy. An estuary that is net heterotrophic has a negative oxygen balance, consuming oxygen and organic matter and releasing CO_2.

Hypoxia Condition of low oxygen concentration (usually <2 mg l^{-1}) in natural waters.

Loading The rate at which a substance is brought into a water body, e.g., from a river.

Pelagic organisms Live in the open water, dissociated from the bottom or the shores.

Phenology The timing of natural events such as metamorphosis or migration.

Plankton Pelagic organisms with weak swimming ability. Most are small. This includes jellyfish and larval forms of most fish and benthic organisms.

Nekton Pelagic organisms with strong swimming ability, including nonlarval fish.

Residence time The average time that a molecule of water or a particle remains in a water body.

Stratification A vertical density gradient in which low-density water overlies higher-density water.

4.22.1 Introduction

As transition zones, estuaries are subject to influences from ocean, atmosphere, and land. Coastal and estuarine ecosystems are particularly sensitive to aspects of climate change, including rising sea level, increasing air temperature, and changing patterns of freshwater runoff (Goberville et al. 2010).

In places where human populations congregate, estuaries provide numerous valuable ecosystem services (Table 1). Estuaries play an essential role in buffering against storms, floods, and drought and in storing and processing nutrients, sediments, contaminants, and other materials. They provide habitat for countless species, including nursery grounds for some marine and anadromous species and feeding grounds for resident and migratory birds, and they support substantial commercial and recreational fisheries for both finfish and shellfish. Estuaries also provide opportunities for recreation and cultural activities. The value of estuaries as public resources is acknowledged by the establishment of reserves such as the US National Estuarine Research Reserve system, and governmental and nongovernmental bodies tasked with stewardship of estuaries.

Estuaries have been severely altered by human activities. Many cities and most ports and harbors are on estuaries. Shorelines have been realigned, and marshes and shoals filled and converted to hard structures such as airports, roads, and residential and industrial areas. The watersheds of estuaries supply water to farms and cities, altering seasonal patterns and quantities of freshwater flow. Rivers and estuaries serve as dumping grounds for waste. Contaminants, including heavy metals, organic toxins, nutrients, and pathogens, are discharged into estuaries. Some estuarine functions have been transformed by introduced species. As a result, many estuaries today would be unrecognizable to an observer of a century ago.

Three themes run through this analysis. First, climate is not the only driver of long-term change. The typical timescale for considering climate effects is up to the middle or the end of the twenty-first century. Over that timescale impacts of human activities in estuaries and their watersheds will intensify. Thus any effect of climate, including changes in regional and local climate, on estuaries can be understood only in the context of regional and local human activities including adaptation to climate effects.

The second theme is the heterogeneity among estuaries. The word 'estuary' is used to describe a diversity of water bodies ranging from coastal wetlands to inland seas, and from fjords to river deltas. They include the mouths of large rivers and isolated basins with no freshwater flow. Some are remote and nearly pristine, whereas others have been altered intensively for human use. Comprehending the scope of long-term change in estuaries as a general class of ecosystems requires careful attention to the unique characteristics of each estuary, and to the ways that climate and local influences will be modified by those characteristics (Canuel et al. 2012).

The third theme is the complex interactions among drivers and mechanisms of long-term change. Responses of estuarine ecosystems are unlikely to be related simply to the proximate influences of climate such as increased temperature.

We start with a discussion of the structure and ecosystem functions of estuaries and how they respond to physical, chemical, and biological influences (see Section 4.22.2), before turning to the important drivers of long-term change (see Section 4.22.3). We then examine the complex responses of estuaries to long-term change and provide a few specific examples by reviewing recent literature for three disparate estuaries (see Section 4.22.4). In Section 4.22.5, we summarize the implications for ecosystems services and management.

4.22.2 What Is an Estuary?

Pritchard (1967) defined an estuary as "a semi-enclosed coastal body of water which has a free connection with the open sea and within which seawater is measurably diluted with freshwater derived from land drainage." This definition, based solely on the physical and geographic features of estuaries, has proved too narrow. For example, many water bodies lacking freshwater runoff behave like estuaries (Potter et al. 2011). Moreover, the regional setting and bathymetry of estuaries may be as important as the degree of dilution by freshwater in determining biological features such as species assemblages (Kimmerer 1991).

Several broader definitions and classifications have been developed (e.g., Engle et al. 2007; Dürr et al. 2011), although no attempt to define such a heterogeneous collection will suit all needs (Elliott and McLusky 2002). For the purposes of this chapter, an estuary is defined as a body of water that: (1) is coastal; (2) is geographically distinguished from the open coast; (3) is permanently or intermittently connected to the

Table 1 Ecosystem services for estuaries based on Costanza et al. (1997). Threats are trends in climate or human activities that negatively affect the provision of that ecosystem service in some estuaries. Mechanisms refer to figures and text in Section 4.22.4.2 (increased temperature, habitat alteration, and increased water demand and nutrient loading are threats to all services but are not listed here)

			Examples of threats		
Service	*Ecosystem functions*	*Examples*	*Climate*	*Human*	*Mechanisms*
Disturbance regulation	Capacitance, damping, integrity of ecosystem response to environmental fluctuations	Storm protection, flood control, drought recovery; habitat response mainly controlled by vegetation structure	Sea-level rise Extreme storms, wind Reduced precipitation	Altered sediment loading Introduced plant species	Sediment (**Figure 3**) Vegetated beds (**Figure 4**)
Nutrient cycling	Storage, cycling, processing, acquisition of nutrients	Nitrogen fixation, nutrient and other elemental cycles	Sea-level rise Reduced precipitation	Increased water demand	Sediment (**Figure 3**) Vegetated beds (**Figure 4**) Eutrophication (**Figure 5**)
Food production	Portion of primary production extractable as food	Production of fish, shellfish, and game by hunting, gathering, fishing, or aquaculture	Reduced precipitation Ocean acidification	Introduced species	Runoff (**Figure 2**) Eutrophication (**Figure 5**) Species (**Figure 6**)
Raw materials	Portion of primary production extractable as raw materials	Production of fuel and other raw materials by harvest or aquaculture	Sea-level rise Storms, wind Reduced precipitation	Overharvest	Runoff (**Figure 2**) Eutrophication (**Figure 5**)
Biological control	Trophic-dynamic regulations of populations	Keystone predator control of prey species, reduction of herbivory by top predators	Sea-level rise Reduced precipitation	Introduced species Altered sediment loading Increased water demand Overharvest	Runoff (**Figure 2**) Eutrophication (**Figure 5**) Species (**Figure 6**)
Habitat/ refugia	Habitat for resident and transient populations	Nurseries, habitat for migratory species, regional habitats for locally harvested species, or overwintering grounds	Sea-level rise Storms, wind Reduced precipitation	Introduced species Altered sediment loading	Runoff (**Figure 2**) Eutrophication (**Figure 5**) Species (**Figure 6**)
Recreation	Providing opportunities for recreational activities	Ecotourism, sport fishing, and other outdoor recreational activities		Introduced species Overharvest	Eutrophication (**Figure 5**) Species (**Figure 6**)
Cultural	Providing materials and opportunities for noncommercial uses	Esthetic, artistic, educational, spiritual, and scientific values of ecosystems		Introduced species Overharvest	Eutrophication (**Figure 5**) Species (**Figure 6**)

open sea; and, has at least one of the following characteristics: (a) seawater mixing with freshwater from a river or groundwater; (b) elevated salinity caused by evaporation; and (c) when the mouth is open, tidal exchange with the ocean.

This definition includes water bodies that range in size from tiny (~1 km^2) salt marshes on arid coasts of western North America, Australia, and Africa to the Baltic Sea (375 000 km^2). Although larger, river-dominated estuaries are permanently open to the sea, a vast number of small estuaries dotting the arid coasts of the world are seasonally or infrequently open to the sea and can be hypersaline (Largier et al. 1997). Freshwater flows into estuaries range from none at all in desert estuaries such as Shark Bay, Western Australia (Smith and Atkinson 1984) to the massive flows of the St. Lawrence, Mekong, and other large rivers. Tides can be minuscule and depend mainly on wind and atmospheric pressure, or they can be driven to a height of many meters by the gravitational effects of the sun and moon. Exchange with the ocean may be mediated mainly by tides or by density-driven circulation as in fjords (Cokelet and Stewart 1985).

Estuaries are often characterized by their high physical energy in the form of tidal currents, wind waves, and freshwater inputs (Nixon 1988). Freshwater inputs and tidal flow also strongly link estuaries to their watersheds, adjacent lands, and the coastal ocean. This linkage transports sediment and dissolved substances such as nutrients and contaminants as well as organisms. Estuaries share some characteristics with each of the linked systems, while retaining some unique characteristics of their own (Elliott and McLusky 2002), many of these related to the interactions of fresh and saltwater in a shallow tidal environment.

The physical complexity of estuarine systems leads to a diversity of habitat types ranging from terrestrial with an aquatic influence (salt and freshwater marshes) to tidally dominated pelagic and benthic habitats. The resulting mosaic can support a high diversity of organisms. In addition, estuaries are often highly productive ecosystems because of high inputs of physical energy from atmosphere, ocean, and land (Nixon 1988). These features often mean that estuarine responses to external influences can be quite strong and complex.

Knowledge of estuaries is based on a rather small subset of the world's estuaries, principally those in more developed countries. This is because research focuses on larger estuaries and those where human impacts have resulted in conflict over resources and services. For example, a search in the Web of Science reveals more than 1000 articles with San Francisco Bay in the title and only 52 with Humboldt Bay, a small estuary in a largely rural area of northern California. This disparity is due to their relative size and the struggle over water, habitat, and other resources in the watershed of San Francisco Bay, which has led to a need for better understanding. This selection bias colors the conclusions of this chapter.

4.22.2.1 Physical Responses of Estuaries to External Influences

The physical configuration and dynamics of an estuary are influenced directly by factors that mediate responses of estuaries to climate change. This discussion focuses mainly on the estuaries with appreciable freshwater flow and tidal currents. Low-flow estuaries are discussed in Section 4.22.2.1.4.

Location is the primary underlying factor that determines the characteristics of an estuary. Latitude constrains regional climate, including storms, precipitation, temperature, and ice cover. Topography of the watershed influences precipitation and runoff. Regional geology and runoff influence the shape and bathymetry of an estuary and the loading, chemical composition, and size distribution of land-derived sediments (Canuel et al. 2012). Orientation of the coast determines regional weather patterns and conditions in the adjacent ocean; for example, the temperate west coasts of all major continents are upwelling regions with moderate ocean temperatures, persistent sea breezes, coastal fog, and dry summer conditions on land. Geographic location (e.g., latitude, continent) determines regional climate and therefore limits the species that could potentially colonize an estuary.

4.22.2.1.1 Tides and Flow

Physical conditions in estuaries respond to the interplay among bathymetry and flows driven by tides, freshwater input, and density differences between fresh water and saltwater. Tidal height at the mouths of estuaries is driven by a combination of astronomical effects (gravitational pull of the moon and sun) and meteorological effects (atmospheric pressure gradients and wind setup). Astronomical tides in the open ocean can range from a few centimeters (much of the Arctic Ocean) to several meters (northeast Atlantic Ocean), but these tides can be greatly amplified or suppressed by interactions with the coast. The dimensions and shape of estuaries can also amplify tidal energy through resonance (e.g., the semidiurnal lunar component in the Bay of Fundy, Garrett 1972) or attenuate it through narrow or shallow choke points (Fernandes et al. 2004).

Tidal flows transport salt, other dissolved and particulate matter, and even plankton and small nekton. Although the principal motion of tidal currents is oscillatory, several mechanisms cause substances and organisms to mix between the ocean and the estuary, and between regions within the estuary. Because of tidal mixing, any property that has a higher (lower) concentration within the estuary than in the coastal ocean will be mixed out of (into) the estuary. This includes any neutrally buoyant, passively moving particles or organisms in the water. However, sediments and other negatively buoyant particles can be trapped in estuaries because they sink. The interaction of tidal flows with sediment deposition, erosion, and transport results in complex geomorphic features such as offshore sand bars, mudflats, and deep channels.

4.22.2.1.2 Freshwater, Salinity, and Mixing

In estuaries with substantial river input, freshwater flow is a dominant control on physical conditions. However, estuaries respond differently to variations in river flow, depending on bathymetry, tidal currents, and wind. River input sets up seaward net flow that carries sediment and other materials and organisms out of the estuary. Freshwater mixes with ocean water, producing a horizontal salinity gradient. Saline water penetrates some distance into the estuary except where extremely high flow moves the salinity gradient into the ocean (e.g., Amazon River plume; Lentz and Limeburner 1995).

Overall, the rate at which estuarine water is mixed or discharged into the ocean determines the minimum rates needed for physical, chemical, and biological processes to be sustained. An estuary with a very high proportional flushing rate and short residence time because of high river flow or strong tides will export much of the river-derived material to the ocean and behave physically as either an extension of the river (if flow is strong) or the ocean (if flow is negligible). Conversely, estuaries with long residence times will retain river-derived materials and chemical and biological processes will be much more under endogenous control.

The salinity gradient produces a tendency for stratification, with low-salinity water at the surface and denser, high-salinity water at the bottom. Although much of the world's ocean is stratified by temperature, salinity has a much stronger influence than temperature on stratification in most estuaries. The extent and frequency of stratification is a key feature of estuarine physics and is used to classify estuaries because of its important role in mixing and transporting substances and organisms (Hansen and Rattray 1966). Stratification is enhanced by high river flow and is suppressed by strong tidal currents and wind, which mix the water vertically. Deep estuaries and deep channels in estuaries tend to stratify more than do shallow estuaries and shoals. For example, fjords are usually permanently stratified (Cokelet and Stewart 1985), whereas shallow lagoons are usually well mixed vertically (e.g., Newton and Mudge 2003).

The degree of vertical mixing or stratification determines the extent of the horizontal salinity gradient and its response to changes in freshwater flow (Hansen and Rattray 1965, 1966; Monismith et al. 2002). In a shallow, narrow, well-mixed estuary (e.g., Hudson River estuary), the salinity gradient moves along the channel in response to both tides and freshwater flow. In deeper regions or deeper estuaries, stratification limits the extent of this movement (e.g., Delaware Bay).

Stratification produces a physical barrier to vertical mixing, isolating the surface from the bottom waters and allowing gravitational circulation, whereby the ebb currents are stronger at the surface and flood currents at the bottom. This is a key mechanism for landward transport of sediment and organisms that sink into the bottom water, concentrating them at the landward end of deep channels or the landward limit of salt penetration (Postma and Kalle 1955). The paradoxical result is that increasing freshwater flow reduces residence time for water but can increase that of sediment and some organisms.

4.22.2.1.3 Other Riverine Inputs: Sediment

River flow brings more than water to an estuary: It carries nutrients, sediment, organic matter, organisms, and in many estuaries, contaminants. Sediment concentration typically increases sharply with increasing river flow. Loading, the product of concentration and flow, is therefore much higher during floods than at other times. Loading of organic matter from land can be an important component of the estuarine carbon budget and is also tied to runoff (Canuel et al. 2012).

Sediment loading to estuaries nourishes geomorphic features such as sand bars, marshes, and mudflats, and also controls the supply of suspended sediment that turns many estuaries turbid. Sediment within an estuary is alternately deposited and resuspended by wind-driven and tidal currents, and mixing with and net flow into the ocean remove suspended sediment.

4.22.2.1.4 Low-Flow Estuaries

Many, and perhaps most, estuaries worldwide have little or no riverine input for at least part of the year, including those in arid regions (e.g., Western Australia, southern Africa, southern California, and Mexico; Largier et al. 1997). In the absence of freshwater flow, tides, wind, and density-driven flow because of the salinity gradient mix estuarine waters with the ocean. These estuaries can fluctuate markedly between states of low salinity during wet periods and hypersalinity during dry periods (Largier et al. 1997), especially if their mouths close during low runoff (Potter et al. 2011).

Estuaries without appreciable river flow may still have a salinity gradient due to groundwater input or net precipitation or evaporation (Largier et al. 1997). These gradients are often sufficient to induce stratification or two-layer circulation, although stratification caused by temperature differences can be important in the absence of a strong salinity gradient.

4.22.2.1.5 Ocean Conditions

Conditions in the coastal ocean can have a strong influence on estuaries through changes in both water level and composition. Along coasts without substantial tidal energy, circulation between estuaries and the ocean is driven by wind, river input, and density gradients. Depending on the orientation and topography around the estuary, coastal wind patterns can influence vertical mixing, horizontal transport, and wind waves (Geyer 1997; Feng and Li 2010). Storms can inundate river mouths and coastal lakes with saltwater, rearrange sediments including sand bars and barrier islands, and provide a significant source of sediment to marshes (Liu 2004; Turner et al. 2006). Estuaries adjacent to upwelling zones can gain much of their productivity from the import of oceanic nutrients and organic matter (Smith and Hollibaugh 1997).

4.22.2.1.6 Vegetated Beds

Most estuarine classifications rely on physical characteristics such as bathymetry, freshwater flow, and stratification (e.g., Hansen and Rattray 1966; Elliott and McLusky 2002; Hume et al. 2007). However, estuaries can be shaped by biological factors, particularly the development of reefs and vegetated beds. Reefs formed by corals, oysters, and other calcifying organisms can alter the shape of an estuary. Mangrove forests, marsh vegetation, and seagrasses alter flow patterns (Nepf and Vivoni 2000) and thereby trap and consolidate sediment. This modifies and stabilizes bathymetry, producing habitat for a variety of species and supporting or concentrating ecosystem processes (Waycott et al. 2009; Polidoro et al. 2010). Mangroves and marsh plants, occupying the land margins of estuaries, provide a valuable buffer against storms and can 'migrate' up or down the land gradient through die-back and growth as conditions change (Simas et al. 2001).

4.22.2.2 Biological Responses of Estuaries to Physical Conditions

Many estuaries support high biological productivity owing to their physical dynamics, shallow depths, and high inputs of nutrients (Nixon 1988). Biological interactions in estuaries can be strong (e.g., Nichols et al. 1990), though sometimes difficult to detect because of the physical variability. Temperature has a direct influence on biota, but most mechanisms by which climate and other external drivers affect estuarine biota are indirect, including residence time, the location of the salinity gradient, stratification, and transport of nutrients, other substances, and organisms from the river and the ocean.

Estuarine habitats can be divided into shallow vegetated beds including marshes, seagrass beds, and mangrove forests, and open-water habitats. Which habitat predominates depends on physical attributes of the estuary such as depth, residence time, sediment supply, tidal range, and freshwater flow. Although there are considerable interaction and movement between these habitats, vegetated beds are essentially terrestrial (although wet), whereas open-water habitats are truly aquatic. In vegetated habitats, space is a resource worth competing over, whereas in open-water habitats resources such as food and nutrients are ephemeral. The key organisms in vegetated beds (i.e., vascular plants that provide the structure) are long-lived and many have limited dispersal capabilities. In open waters, the key producers are microbes with lifetimes of hours to days, and dispersal is rapid even for most benthic organisms which have planktonic larvae. This discussion excludes coral reefs, which have characteristics of both of the preceding classes.

Estuarine species are most abundant over a particular range of salinity and less abundant where salinity deviates from that range. Plankton and nekton live in a moving frame of reference and therefore move with the salinity gradient. Benthic organisms and marsh vegetation may take weeks, months, or even years to adjust to a changed salinity distribution by dying back where conditions are unfavorable and colonizing favorable areas.

An estuary with short residence time caused by strong tidal mixing or high freshwater flow may support small plankton species only if they have very rapid population growth (Rogers 1940), although many estuarine animals have swimming patterns that overcome these losses (Cronin and Forward 1979). At intermediate rates of mixing, the abundance of phytoplankton may be directly related to residence time (Jassby et al. 2002). Increasing freshwater flow may stimulate phytoplankton production through increased nutrient loading (Nixon 1988; Mallin et al. 1993) or through enhanced stratification that traps phytoplankton in well-lit surface waters (Cloern 1984). By these mechanisms, phytoplankton production can either increase or decrease with freshwater flow, and these responses can occur in the same estuary. For example, in the San Francisco Estuary (SFE) phytoplankton biomass varies inversely with flow through residence time in the freshwater region (Jassby et al. 2002), positively with flow through stratification in South San Francisco Bay (Cloern 1984), and is unresponsive to flow in the low-salinity region of the northern estuary (Kimmerer et al. 2012).

Stratification not only stimulates phytoplankton growth, it also traps settling phytoplankton and other organic matter in the deep waters of an estuary, where microbial respiration can result in hypoxia, limiting the suitability of these areas for many organisms (Diaz 2001; Conley et al. 2009). When phytoplankton biomass is high and the estuary is eutrophic because of the combination of nutrient loading and stratification, the resulting turbidity can inhibit the growth of plants such as seagrasses through light limitation (Short and Neckles 1999). In some estuaries suspended sediments limit penetration of light into the water and thereby limit production of phytoplankton and rooted plants even when nutrient concentrations are high (Cole et al. 1992; Goosen et al. 1999).

The abundance of planktonic animals and small nekton may vary with freshwater flow because of changes in phytoplankton biomass. Abundance may increase with flow because stronger stratification causes higher retention of species that swim into deeper water or migrate in synchrony with tidal currents (Cronin and Forward 1979). Up-estuary transport of young crabs and shrimp could be enhanced, resulting in higher survival, when high freshwater flow causes increased landward flow of seawater near the bottom (Schlacher and Wooldridge 1994; Kimmerer 2002). Abundance may also vary with residence time as for phytoplankton. Transport of the young of anadromous species such as striped bass and salmon from the river to the estuary may be enhanced by high river flow (Stevens and Miller 1983).

4.22.2.3 Human Influences

Most of the world's coastal cities are on estuaries, and many estuaries have been heavily modified to support human activities (e.g., Nichols et al. 1986; Lotze 2010). Marshes (Day et al. 2008) and mangrove forests (Polidoro et al. 2010) have been destroyed for development, resulting in extensive losses of estuarine habitat as well as increasing risk of shoreline erosion. Shorelines have been modified further by the installation of docks, jetties, and hard barriers such as levees, seawalls, and tidal gates (Nienhuis and Smaal 1994). These physical alterations together with channel dredging and dredge disposal amend the response of an estuary to tides, freshwater flow, and storms.

Land use in the watershed can have substantial impacts on an estuary. Extensive agriculture and urban development demand freshwater, cause erosion, and increase peak flows during storms. Diversion of freshwater from the watershed and impoundment of water behind dams reduce the rate and dampen the seasonal pattern of freshwater flow into estuaries (Poff et al. 2007). In addition, rivers and estuaries can be starved of their sediment supply by trapping behind dams (Schoellhamer 2011).

Some of the freshwater diverted from watersheds and estuaries is lost to evapotranspiration and some returns as discharge from farms, wastewater treatment plants, and industrial facilities (or returns elsewhere as precipitation). Eutrophication from nutrients and organic matter in point-source (wastewater treatment plants) and non-point source (agricultural and urban runoff) discharge is the predominant cause of environmental degradation in many estuaries (Cloern 2001).

These human influences have numerous repercussions for estuarine biota, many of which are discussed in Section 4.22.4.2. In extreme cases, dams and diversions can starve estuaries of freshwater, resulting in a complete reorganization of ecosystems (e.g., Colorado River estuary; Kowalewski et al. 2000). Similarly, estuarine ecosystems can be severely degraded by extensive hypoxia, resulting in the loss of valuable species (Diaz 2001). The global movement of species through shipping (in ballast water or cargo or attached to ships) and other activities is homogenizing biota across oceans (Ruiz et al. 1999).

4.22.2.4 Ecosystem Functions and Services

A variety of ecosystem functions and services can be attributed to estuaries (Table 1). We take an inclusive view of ecosystem services beyond those that have a market value (Norgaard 2010).

Estuaries serve as corridors linking land to sea. They supply water, nutrients, and organic matter to the coastal ocean and supply sediment, including most of the sand that forms beaches in temperate zones. Estuaries and in particular their vegetated beds act as a filter, dampening variation in riverine and oceanic sources of materials and removing or burying contaminants (Klamer et al. 1994; Dürr et al. 2011).

Important nutrient cycling processes in estuaries can include nitrogen fixation (Howarth et al. 1988), denitrification (Seitzinger 1988), uptake, remineralization, and sequestration in plants and sediments. Some estuaries are net autotrophic in that they consume inorganic nutrients and CO_2, producing organic matter that is either buried or exported to the coastal ocean (Kemp et al. 1997); some are net heterotrophic (Smith and Hollibaugh 1997); whereas others are close to balance (Smith and Hollibaugh 2006).

Storage of materials within an estuary generally increases with residence time of the water and with the strength of trapping of sediments by estuarine currents. Growth of organisms resident in an estuary results in storage of some of this material in their biomass, with turnover times that can be much longer than that of the water. Sediments form another pool for nutrients, contaminants, and other substances with an even longer turnover time than that of most organisms. Sediments may become buried, sequestering these materials, or they may be exported to the coastal ocean during periods of tidal or storm-driven erosion.

Estuaries provide habitat for a variety of organisms, in particular nursery habitat for many marine and anadromous species. Most estuaries support potentially large populations of mollusks, crustaceans, and finfish, and many also support marine mammals and large populations of birds. Anadromous fish such as salmon and sturgeon use estuaries as rearing habitat and for passage to and from spawning grounds.

4.22.2.5 Estuaries as Islands

Some of the most severe effects of global warming have occurred on mountaintops where low-lying areas form a barrier to species' range extension and thereby isolate species' populations (Parmesan 2006). Mountaintops in this case are effectively islands with limited dispersal for these species. Estuaries may function as islands in that the coastal ocean may be inhospitable to some species because of high salinity, long distances between estuaries, or adverse current patterns. Genetic divergence among populations of copepods in estuaries along the Atlantic coast of North America (Caudill and Bucklin 2004; Milligan et al. 2011) and among populations of gobies in California estuaries (Earl et al. 2010) suggests limited dispersal among estuaries for these organisms. Other case studies indicate high connectivity, such as between estuarine populations of copepods in California and Mexico (Trujillo Ortiz et al. 1995) and amphipods in New Zealand (Stevens and Hogg 2004).

Resident species in isolated estuaries may be vulnerable to local extirpation. For example, populations of several diadromous fishes in the North Atlantic basin, including Atlantic salmon, have been extirpated from estuaries through a combination of climate and local anthropogenic effects (Limburg and Waldman 2009). No examples have been reported to date of extinction of estuarine species caused by climate change.

4.22.3 Long-Term Change

This section discusses direct effects of climate change and of other, mostly anthropogenic long-term changes. For each mechanism of long-term change, we assess the likely magnitude of the effects on estuaries to provide a means of comparing among these effects and assessing their relative importance. Although direct effects of both climate and human intervention have been observed and are forecasted to grow, indirect effects and interactions among these effects may be more important at the level of individual ecosystems, as discussed in Section 4.22.4 Modes of Estuarine Response.

4.22.3.1 Climate Change

Of the many ways that climate Change may influence estuaries, three are consistently present in model forecasts and observed in historical records and are likely to affect most estuaries (Table 2, Figure 1). Global mean air and ocean temperatures are predicted to continue rising, although with considerable variability, and some areas will even cool (e.g., upwelling zones). Sea-level rise is also global, but heterogeneous and modified locally by tides and weather. Ocean acidification is pervasive, although several processes may offset its effect in estuaries.

Other modes of global climate change are either more spatially and temporally sporadic than the preceding three, or their historical and forecasted trends are less certain (IPCC 2007). In particular, precipitation, storm intensity, and wind speeds will increase in some areas but not in others.

4.22.3.1.1 Temperature Increase

Temperature exerts a fundamental control on biochemical rates in ecosystems and on physiological rates in most marine and estuarine organisms. Biogeochemical rates such as nutrient cycling generally increase with temperature. Solubility of oxygen in water decreases as temperature rises, so that less microbial respiration is required to reach a hypoxic condition. At the same time, respiration increases with increasing temperature at a higher rate than does photosynthesis, so that microbial processes will consume more oxygen (Lopez-Urrutia et al. 2006). The overall effect is a trend toward net heterotrophy and an increased incidence of hypoxia in estuaries. Warming may also contribute to the formation of harmful algal blooms, which appear to be increasing in water bodies worldwide (Paerl and Huisman 2008).

Rates of processes such as respiration and consumption increase with temperature up to a point beyond which they fall off rapidly toward the upper lethal temperature (Pörtner 2002). The setpoints and temperature sensitivities vary among the physiological processes and with species and acclimatization history. Below the peak, rising temperature causes positive responses of consumption, nutrient uptake and release, reproduction, growth, and development, while at the same time mortality rates increase as predators, pathogens, and

Table 2 Projected long-term changes in estuaries relative to current conditions. Quantitative projections are in the middle of the range; see Section 4.22.3 for sources. Causes in bold are those with supporting evidence and consistent trend in many estuaries. Projections listed as "Regional" refer to increases in some areas and decreases in others; those listed as "Variable" have trends with less statistical support than, for example, temperature. Consequences exclude interactions among causes and effects (see Section 4.22.4.2 Interactions).

Cause	*Projection to 2100*	*Potential consequences for some estuaries*
Temperature rise	3 °C	Change in phenology, range of estuarine species Species introductions and extirpations Reduced survival, reproduction, and growth of desirable species
Sea level rise	1–2 m	Reduced growth rate of submerged vegetation Increased erosion of shorelines, mudflats, and marshes Increased inundation of shore Increased salt penetration, species changes Increased strength of tidal currents
Acidification	+0.3 pH units	Impaired calcification of bivalves
Total precipitation	Regional	Possible increase in extreme floods and droughts
Timing of runoff	Regional, earlier	Shift to earlier runoff peak where dominated by snowmelt
Wind speed	Variable	Increased erosion with increased wind speed; increased upwelling
Storm Intensity	Variable	Increased erosion, flooding
Catastrophic change		Breaches of levees or barrier islands due to storms may alter physical configuration Shifts to alternative stable ecosystem states
Dams in watershed	Increases in less developed areas	Reduction in total freshwater flow, alteration of seasonal hydrograph
Dredging/armoring	Regional increase	Increase in erosional power in unarmored areas, loss of sediment for marshes
Population growth	Regional increase	Increased demand for ecosystem services; increased urbanization
Water demand	Regional increase	Decreased inflow and increased salinity
Sediment loading	Regional decrease	Increased water clarity, erosion Increased loading with storm intensity, decreased water clarity, deposition
Habitat alteration	Regional increase	Elimination of vegetated areas, degradation of others
Nutrient & organic loading	More eutrophication	Hypoxic areas, harmful algal blooms
Harvest	Regional increase	Alteration of trophic structure
Species introductions		Difficult to predict; depends on what species and where

parasites increase their metabolic rates. Thus, the vital rates of birth and death for any population vary nonlinearly with temperature, and no two populations respond the same way. Sharp changes in relative abundance are likely because of these differential responses to temperature among the species in an estuarine assemblage.

Temperature also affects organisms directly through their phenology, and this effect could be significant for estuarine species, although there are few reports of phenological shifts from estuaries and coastal environments. Photoperiod has an equally strong influence on phenology, and as spring warming comes earlier and fall cooling later, various organisms may receive conflicting signals from temperature, season, and sunlight, and reproductive success may decrease (Lawrence and Soame 2004). For example, a delay in reproduction of autumn-spawning limpets because of higher temperature resulted in recruitment failures (Moore et al. 2011).

Increases in temperature at one location may result in extirpations but favor populations of species with higher thermal maxima. At a larger scale the net result is poleward movement in the ranges of species that can cross the intervening ocean. Such range shifts have been observed in open-ocean phytoplankton, zooplankton, and fish (Mantua et al. 1997; Reid et al. 1998; Beaugrand and Reid 2003; Perry et al. 2005). Range shifts in invertebrates of rocky shores in central California have been linked to increasing temperature (Sagarin et al. 1999). High-latitude estuaries and coasts will lose ice cover and the intense spring bloom of ice algae will give way to a more diffuse bloom of phytoplankton, cutting off much of the food supply to the benthos (Grebmeier et al. 2006).

Case studies in estuaries show some evidence of range shifts in response to warming. A northward shift in distributions of predatory marine species in response to decadal-scale climate fluctuations may have induced a trophic cascade in the SFE (Cloern et al. 2007). Encroachment of tropical species of fish into a South African estuary apparently was driven by increases in temperature (James et al. 2008). A similar pattern was observed in seagrass meadows of the northern Gulf of Mexico (Fodrie et al. 2010). However, no shifts were seen in invertebrates on rocky shores of eastern Australia over 50 years despite measurable warming (Poloczanska et al. 2011). A meta-analysis showed no clear evidence of range shifts in marine, estuarine, and freshwater fishes in Australia, although the authors of that study acknowledged the difficulty of determining ranges of such highly mobile species (Booth et al. 2011). The paucity of reports of range shifts in estuaries may reflect the paucity of studies or an actual lower rate of range contraction or expansion in estuaries compared to other ecosystems.

4.22.3.1.2 Sea-Level Rise

Global sea-level rise has been estimated to accelerate and to reach 1–2 m by 2100 (Vermeer and Rahmstorf 2009).

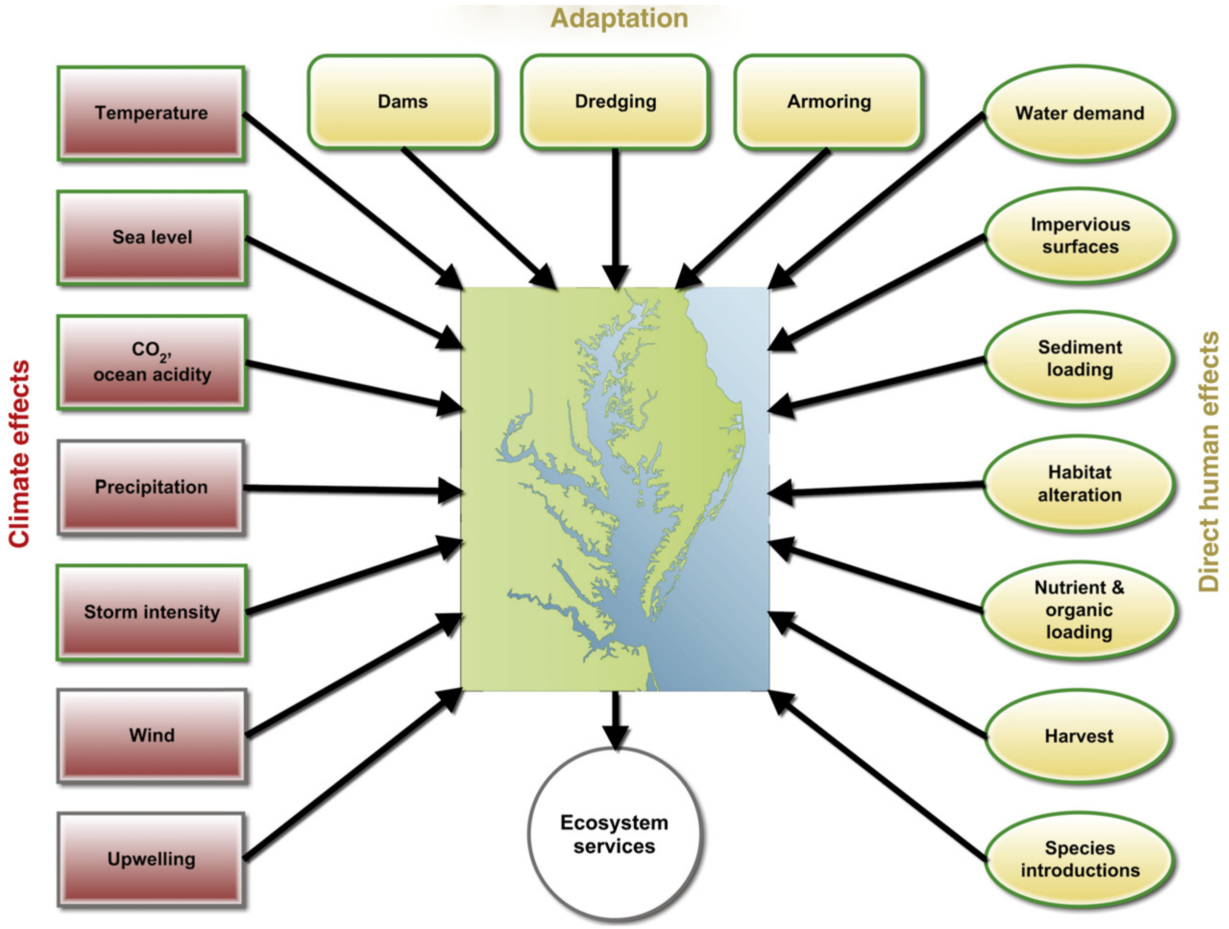

Figure 1 Schematic of significant long-term influences on a generic estuary, represented here by the Chesapeake Bay. Each box is a potential influence on estuarine functions or the provision of estuarine services. Rectangular boxes on the left-hand side are climate effects, ovals on the right-hand side are human activities, and rounded rectangles at the top are human adaptations to climate, and other long-term, changes. Green borders indicate a positive trend in some regions. Gray borders indicate a positive or negative trend. Black arrows indicate causative relationships between influences and ecosystem responses that may be positive or negative. Table 2 gives additional details about mechanisms underlying some of these relationships.

However, locally the rise is amplified or offset by erosion, accretion, or vertical movements of the earth's crust (Peltier 1999). For example, the Mississippi Delta is losing land area because of sea-level rise coupled with a reduction in sediment supply in the Mississippi River caused by dams. Rising relative sea level will have numerous direct effects and many indirect effects on estuaries. The most obvious effect would be inundation of lands that are now dry and conversion of intertidal habitats to subtidal. For example, the area inundated by the 100-year flood in San Francisco Bay at a 50-cm higher sea level would include about 35 000 ha of nearshore lands, of which about half is developed and half is grassland (Knowles 2010).

The consequences of sea-level rise are difficult to predict in a given estuary. First, high tides are likely to increase more than mean sea level through frictional effects, and this effect would be exacerbated by any increase in tidal resonance, storm surges, and freshwater floods (Cayan et al. 2008). Second, increasing sea level will alter sediment transport through erosion, deposition, and changes in circulation patterns, resulting in a change in bathymetry that is difficult to predict without accurate sediment-transport models. Third, trapping of sediment by vegetated areas such as marshes and seagrass beds and upslope migration of marshes and mangrove forests will alter the outcome of rising sea level. Finally, human populations will not remain passive to rising sea level, but will armor shorelines with levees and seawalls.

4.22.3.1.3 Acidification

Ocean water resists changes in pH through a buffering system in which dissolved CO_2 is in chemical equilibrium with hydrogen, bicarbonate, and carbonate ions. Since the beginning of the industrial age about 40% of the net release of CO_2 into the atmosphere has dissolved in the ocean (IPCC 2007). This increase in dissolved CO_2 has shifted the equilibrium to make the ocean more acidic by 0.1 pH, and projections are for a further reduction by 2100 of $\sim$0.3 pH units (Caldeira and Wickett 2003), a 2.5-fold increase in acidity.

The decrease in ocean pH will cause dissolution of, and increased metabolic cost of producing, hard parts of calcareous organisms including corals and bivalves. The most prominent effect is the reduction in calcification by corals, which can slow their growth and kill reefs (Orr et al. 2005). Oyster, clam, and mussel beds and several groups of open-ocean plankton are also likely to be affected severely and rather unpredictably. For example, two species of oyster that were exposed experimentally to different levels of atmospheric CO_2 had very different responses in growth and shell formation (Miller et al. 2009).

Research since the IPCC report (2007) reveals that a wide variety of organisms may suffer negative physiological effects from acidification (Fabry et al. 2008), although effects on noncalcifying organisms may not be severe (Hendriks et al. 2010). Ecological effects of acidification have scarcely been addressed.

The pH along coasts and in estuaries is subject to influences not prominent in the open ocean, notably inputs of wastewater, freshwater, sediment, acids, and bases, as well as local biological processes, particularly microbial production and respiration, that alter total CO_2 concentrations. Upwelled water is initially supersaturated with dissolved CO_2 and low in pH, although pH increases with time at the surface (Fassbender et al. 2011). Estuaries generally are sources of CO_2 to the atmosphere because of a combination of net heterotrophy, eutrophication, and discharges from wastewater treatment plants (Caffrey 2004; Borges et al. 2006; Feely et al. 2010; Cai et al. 2011).

4.22.3.1.4 Storms and Precipitation

The rising heat content of the oceans adds moisture and energy to the atmosphere and will increase the frequency or strength of storms (Knutson et al. 2010), but regional weather responses are rarely known. Nevertheless, future precipitation and the frequency and intensity of storms are less well constrained in global climate forecasts than are temperature, sea level, and acidification (Nijssen et al. 2001; Trenberth et al. 2003). Regional projections of annual precipitation using downscaled climate models differ even in the direction of the trend. The response of precipitation to ocean-scale climate forcing such as the El Niño-Southern Oscillation (ENSO) is informative: El Niño patterns bring wet conditions to northwestern North America and dry conditions to southern California and western Mexico, and central California can be either wet or dry (Cayan et al. 1999). Where much of the runoff comes from melting of snow or glaciers, the warming trend will lead to earlier runoff peaks. This is both observed and forecasted for wide areas of western North America where much of the annual runoff is from snow melting in high mountains (Aguado et al. 1992).

Violent storms can have a wide variety of physical effects on estuaries that depend on orientation of the coast, elevation, and vulnerability of coastal features to overtopping or scour. Infrequent, powerful storms may be important in supplying sediment to coastal marshes and beaches (Turner et al. 2006). Even in the absence of geomorphic effects, storms can cause flooding and temporary transformation of estuaries into freshwater systems, or coastal lakes into saline systems (Paerl et al. 2001; Liu 2004).

4.22.3.1.5 Wind and Upwelling

Atmospheric pressure gradients responsible for wind are likely to intensify with increasing temperature gradients and storm intensity. The direct influence of wind on estuarine dynamics depends on water depth and wind direction (see Section 4.22.2.1.5 Ocean Conditions.). On the West coasts of continents an increase in wind strength is likely to result in an increased frequency and intensity of upwelling (Snyder et al. 2003), potentially increasing the loading of nutrients and organic matter to estuaries.

4.22.3.2 Direct Human Effects

Human population is likely to continue growing, although at a declining rate (United Nations 2004). At least for some time in some countries this growth will be accompanied by increasing standards of living resulting in an increase in efficiency of agriculture and a shift in the economic basis from agriculture to industry. More people will live in cities and around estuaries. Increasing urbanization, together with increasing demand for water, land, and food, will increase demand for estuarine services and have negative impacts on estuaries (**Figure 1**, **Table 2**).

Globally, forecast shortages of water are more likely to arise from increasing demand as human populations grow than from decreasing precipitation (Vörösmarty et al. 2000). Current shortages in arid regions will be exacerbated. Major river systems that form or cross international borders include the Amazon, Nile, Mekong, Brahmaputra, and Tigris-Euphrates, many of which have substantial dams in place or under construction. Although minimum flows are legally mandated in many rivers and estuaries (e.g., SFE; Kimmerer 2002), such mandates are difficult to maintain where rivers cross borders, as in the Colorado River estuary (Kowalewski et al. 2000).

The increasing conversion of land to support the growing human population will result in more destruction of marshes and mangrove forests for farming, urban development, and biofuel (Polidoro et al. 2010). Some shifts in land use, such as intensification of agriculture, and limits on water supply are likely to lead to further increases in use of fertilizer and agricultural chemicals (Tilman et al. 2001). The resulting increase in nutrient loading to estuaries will worsen eutrophication (Nixon 1995; Tilman et al. 2001).

Sediment inputs to estuaries likely will be reduced in most areas of the world. Dams trap sediments, causing erosion in rivers downstream (Kondolf 1997) and limiting sediment supplies for maintaining estuarine marshes (Blum and Roberts 2009), with consequent erosion in estuaries as seen in the Nile and Mississippi Deltas. The reduction in sediment supplies to river-dominated estuaries will cause turbid waters to clear (Schoellhamer 2011), contributing to algal blooms and exacerbating any tendency toward eutrophication.

The human demand for food will increase fishing pressure, even with more comprehensive management and regulation of fisheries. Already overfishing has caused reorganization of oceanic and coastal ecosystems through removal of top predators (Scheffer et al. 2005), and additional effects are being seen as fishing effort shifts to smaller fish at lower trophic levels (Pauly et al. 1998). A worldwide increase in abundance of jellyfish in oceanic and coastal waters may be caused by removal of competition by fish, along with warming (Purcell 2005; Purcell et al. 2007). Jellyfish contribute little to fisheries.

Shoreline modification will accelerate, leading to installation of more hard edges and barriers (Bulleri and Chapman 2010). Armoring shores with seawalls and levees may accelerate as part of a strategy of adaptation to rising sea level, particularly in low-lying areas (Nicholls and Cazenave 2010). Armored shores can lead to increased and focused wave and tidal energy, causing erosion along unprotected shores. Restoration of marshes also alters shorelines, although it is generally done to improve or enhance estuarine ecosystems (Callaway 2005).

The increase in global population and trade has caused an increase in worldwide shipping and that trend is expected to continue. Besides the requirement for expansion of port facilities, shipping brings an unavoidable risk of accidents and oil spills that damage estuaries, especially marshes and other intertidal areas.

Global shipping also transports species between estuaries (Carlton and Geller 1993; Ruiz et al. 1999, 2000). Although regulations that require treatment of ships' ballast water may be effective in reducing this transport, the increase in shipping, particularly into ports that lack regulations or enforcement, will allow more transport of organisms. Certain introduced species have altered the physical structure of estuaries, notably plants that create dense beds (e.g., cordgrass; Callaway and Josselyn 1992; Crooks 2002; Levin et al. 2006; Silliman and Bertness 2004). Some bivalves, including the zebra mussel (Caraco et al. 1997) and the clams *Corbicula fluminea* (Phelps 1994) and *Corbula amurensis* (Nichols et al. 1990), have had strong impacts on water-column organisms through predation and competition. Other taxonomic groups have had big impacts (Purcell et al. 2007; Lehtiniemi and Gorokhova 2008), and the native faunas of some estuaries have been overwhelmed by introduced species (e.g., SFE, Cohen and Carlton 1998).

A catastrophic change in the physical configuration of an estuary has a low probability of occurring in any one year, but over a timescale of many decades it can become likely. For example, by definition a 100-year flood has a 1% probability of occurrence in any one year and is likely to occur at least once in the next 70 years. Catastrophes that can be anticipated include geomorphic rearrangement by large storms (Morton and Sallenger 2003), earthquakes (Mount and Twiss 2005), and tsunamis (MacInnes et al. 2009). These changes may or may not be reversible through intensive human intervention such as by repairing breaches in levees or seawalls.

4.22.4 Modes of Estuarine Response

The responses to long-term change are likely to differ greatly among estuaries in different regions. Some regions will see an increase in precipitation and others a decline, some regions will be harder-hit by strong storms than others, and rivers in some mountainous watersheds will see a shift to more runoff in winter and less in spring. The rate of sea-level rise will depend on local or regional vertical movements of the earth's crust. Estuaries at high latitudes will have a longer ice-free season. Estuaries in upwelling zones will receive a higher input of nutrients as upwelling strengthens.

The unique physical and geographic configuration of each estuary also influences its response to long-term change. For example, estuaries formed from river-derived sediment such as deltas and bar-built estuaries are particularly vulnerable to changes in freshwater flow, impoundment of sediments, sea-level rise, and alteration of longshore sediment transport by ocean waves. The ability of an estuarine species to extend its range depends on the distance to adjacent estuaries, outflow patterns, and ocean currents, as well as its ability to survive oceanic conditions.

The relative importance of climate and other anthropogenic effects will depend on the extent of human use of an estuary. Where estuaries or their watersheds have been extensively altered for human use, trends in human demand for freshwater, food, and land will be a key determinant of long-term change. In addition, human adaptation to climate change will entail alterations that also influence ecosystem function.

Moreover, changes that are expected within any one estuary will be concurrent, and their effects will interact (see Section 4.22.4.2. Interactions). These interactions are likely to play out in different ways in different estuaries.

Some likely differences among the responses of estuaries to climate change can be inferred from their heterogeneous responses to seasonal (somewhat predictable) and interannual (unpredictable) variation in inputs. For example, estuaries showed widely varying seasonal and interannual patterns of phytoplankton production, probably reflecting different controls on productivity (Cloern and Jassby 2008, 2010). Likewise, estuarine organisms can respond to freshwater flow by a wide variety of mechanisms that can even be of opposite sign (see Section 4.22.2.1.2 Freshwater, Salinity, and Mixing; Kimmerer 2002; Gillanders and Kingsford 2002).

Estuarine scientists usually study only one or a few estuaries, and comparisons among estuaries are valuable but infrequent (e.g., Boynton et al. 1982; Nixon 1988; Seitzinger 1988; Emmett et al. 2000; Cloern and Jassby 2008, 2010; Gillanders et al. 2011). This emphasis on particular estuaries reflects the heterogeneity among estuaries, their different responses to climate and other influences, and the differences in research topics. For example, eutrophication is arguably the process of greatest management concern in many estuaries in Europe and eastern North America, and therefore receives a lot of research attention. Eutrophication is much less prevalent, and therefore less often studied, in estuaries in western North America. The heterogeneity among estuaries and among the topics studied limits the scope of general statements on the effects of climate change on estuarine ecosystems.

4.22.4.1 Mitigation and Adaptation

Mitigation activities that affect estuaries directly include increases in the generation of renewable energy by dams and tidal and wave generators or by production of biofuel through harvesting or aquaculture. Each of these can exact penalties to the functioning of estuarine ecosystems. Dams alter hydrographs, and tidal and wave generators can kill estuarine organisms (Aprahamian et al. 2010). The use of large-scale coastal aquaculture to raise food or biofuels requires a large area with attendant loss of habitat and potential for eutrophication.

Adaptation in this context refers to actions to reduce deleterious effects of climate change at a local or regional scale (Scheraga and Grambsch 1998; Nillesen and van Ierland 2006). This may include abandoning areas that become unlivable because of changing climate, which is already

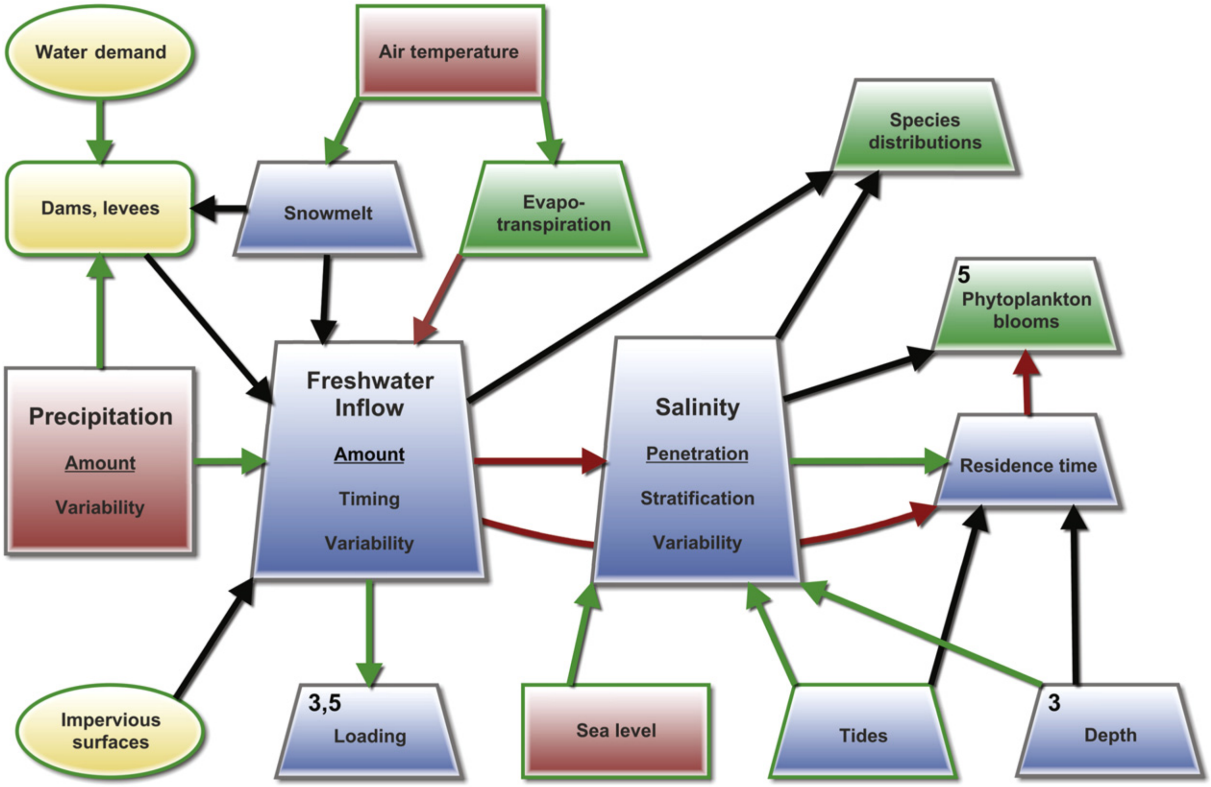

Figure 2 Schematic of the physical and biological responses of an estuary to changes in 'precipitation and freshwater runoff,' as described in Section 4.22.2.1 Physical Responses of Estuaries to External Influences. Boxes as in **Figure 1** plus blue trapezoids are physical responses to external influences including the 'salinity' gradient. Green trapezoids are biological responses, perhaps mediated by physical responses. Border colors as in **Figure 1**. Black arrows as in **Figure 1**. Green arrows indicate a positive effect as the influence increases. Red indicates a negative effect, which refers to the underlined quantities in the center boxes. Numbers in boxes link responses to other figures where processes are detailed.

occurring in the Mekong Delta and elsewhere (de Sherbinin et al. 2011). Less extreme measures include armoring to protect property against erosion caused by rising sea level and more powerful storms. In agricultural watersheds, adaptation to higher temperature and increased drought frequency may require increasing irrigation flows, further increasing demand for water, unless improvements in irrigation practices offset this increase. Desalination to offset loss of freshwater flow requires power and the disposal of brine.

Many adaptations will entail changes in policy and exacerbate conflict over dwindling resources, particularly where estuaries and their rivers cross international borders. Policy changes could include abandonment or reduction of environmental protection in favor of protecting human life and property, resulting in devastating alterations to estuaries.

4.22.4.2 Interactions

In general, the anticipated long-term changes in climate and human influences are clear (see Section 4.22.3); the processes that control estuarine responses to those influences are understood in broad terms (see Section 4.22.2). However, these effects will not occur in isolation. The network of interactions among climate variables, other long-term trends, and physical and biological responses are complex and our summary of interactions is necessarily simple and incomplete. Each subsection proceeds generally from the immediate effects of climate forcing, to the effects of human activities, and then to the interactions.

4.22.4.2.1 Precipitation, Freshwater Runoff, and Salinity (Figure 2)

Climate and human activities influence the temporal pattern and quantity of runoff into estuaries, with numerous ramifications for ecosystem function. Annual precipitation, timing of runoff peaks, and variability because of seasonal patterns and storms, all of which can have climate-based trends, determine the water available for runoff. Rising temperature will increase evapotranspiration, which increases uptake of water by plants from groundwater, reducing flow into estuaries (Nijssen et al. 2001).

Increasing demand for water, increased evapotranspiration, and seasonal shifts and unreliability in precipitation will stimulate construction of dams to capture more water for times of low flow. Although dams dampen seasonal variability in freshwater flow, greater variability in precipitation and construction of impervious surfaces and levees will increase short-term variability by hours to days. Local diversions of water from rivers and groundwater pools will further deplete the water available to flow into estuaries, especially during droughts.

Changes in runoff will be accompanied by changes in loading of materials such as sediments and nutrients. However, these loadings in general are more influenced by regional or local human activities such as dams and agriculture than by changes in flow patterns.

Changes in freshwater flow into estuaries have numerous consequences, and numerous causal pathways to those consequences (see Section 4.22.2.1.2.). The influence of freshwater flow on salinity patterns in an estuary depends on bathymetry, sea level, tides, and wind speed and direction. Rising sea level would increase salinity in the absence of other changes but in most estuaries it probably has a minor influence on long-term change compared with alterations in flow and bathymetry.

The physical changes associated with increasing freshwater flow induce a cascade of biotic responses. In tidal freshwater regions flow directly influences distributions and residence time of organisms. In more saline areas the influence of flow is mediated by salinity. Shifts in the salinity gradient alter the distributions of benthic and marsh biota through salinity tolerance and species interactions such as predation and competition. While pelagic species are less affected by the movement of the salinity gradient because they move with the water (Laprise and Dodson 1993), high flows can flush pelagic organisms from an estuary and diminish their estuarine populations.

Variation in freshwater flow into estuaries affects phytoplankton production (see Section 4.22.2.2), which is the predominant source of available organic carbon for most estuarine ecosystems. In many river-dominated estuaries, freshwater flow stimulates primary production. Fish and large invertebrates may grow and reproduce faster if high flow stimulates primary production, increasing production up the foodweb. Alternatively, estuarine animals may respond to changes in physical habitat; for example, through retention mechanisms or changes in the overlap of favorable salinity with favorable bathymetry (Kimmerer et al. 2009).

4.22.4.2.2 Sediment Supply, Transport, and Loss (Figure 3)

River flow controls much of the loading of sediment into an estuary (see Section 4.22.2.1.3.). Sediment loading may increase with an increase in peak river flows, or under dry conditions with an increase in the frequency of fires that expose land to greater erosion. Dredging, mining, and construction of hard or impervious surfaces in the watershed can increase sediment loading. In many of the world's rivers, though, the predominant trend is likely to be a decrease in sediment loading because of the construction of dams that trap sediments.

Within an estuary the short-term balance between erosion and deposition is controlled by the strength of tidal and river-derived currents and wind waves and how these interact with bathymetry. Sea-level rise, an increase in wind speed or peak storm intensity, armoring as a defense against local erosion, and dredging will shift this short-term balance toward erosion.

The long-term balance between supply and loss to the ocean and to burial within the estuary depends on the short-term balance, which governs how much of the sediment is suspended in the water (Schoellhamer 2011). The long-term balance also depends on residence time of suspended sediment in the estuary. Sediment can be trapped by two-layer estuarine circulation, which usually increases with freshwater flow and with increasing water depth (see Section 4.22.2.1.2.). Estuaries that are open only seasonally may remain open for longer periods as the sand supply dwindles and peak wave height increases, although decreasing river flow may shorten the open period.

Turbidity caused by suspended sediment can limit growth rates of plants, including phytoplankton and seagrass (Goosen et al. 1999). Turbidity also interferes with visual detection of prey by predators, creating a refuge for the prey (De Robertis et al. 2003). Increasing water depth caused by tidal scouring of channels, in some places accelerated by dredging, can change tidal circulation, salt balance, and the movement and retention of planktonic and epibenthic organisms (Hansen and Rattray 1965; Monismith et al. 2002).

4.22.4.2.3 Vegetated Beds (Figure 4)

Marshes, mangrove forests, and seagrass beds exist in a dynamic equilibrium of sediment erosion and deposition. Long-term changes in factors that affect sediment budgets (see Section 4.22.4.2.2.) are essential to the development and stability of vegetated beds. Conversely, vegetated beds reduce current speed and wave height, capturing sediment and resisting erosion.

Accretion of marshes is faster where sediment supply is adequate and the tidal range is large enough to transport the sediment quickly (Simas et al. 2001). If the sediment supply is inadequate for marsh elevation to keep up with rising sea level, marshes may 'move' up-slope as upland is replaced by marsh and low marsh by open water. However, this will be limited in many estuaries by the slope of the land and the extent of hardened shoreline (Osterkamp et al. 2001; Chust et al. 2011).

Vegetated beds are vulnerable to other effects. For example, seagrasses may be affected simultaneously by increased CO_2 and temperature, which enhance growth; increased sea level, which decreases light availability; increased strength of tidal currents; and increased salinity penetration, which limits the range of seagrass beds through physiological tolerance (Short and Neckles 1999). However, local anthropogenic impacts such as habitat destruction, nutrient loading, and sediment discharge may cause a much greater loss of submerged and marsh vegetation than climate change. Nutrient loading can stimulate phytoplankton blooms which reduce light penetration and degrade vegetated beds. Direct human impacts have devastated seagrass beds in some areas (Orth et al. 2006), and a recent estimate of global rate of loss was an astonishing 7% per year (Waycott et al. 2009). Similar rates of loss apply to mangrove forests, with the principal cause being development (Polidoro et al. 2010). In both cases, valuable ecosystem services such as nutrient cycling and shoreline protection are lost.

4.22.4.2.4 Eutrophication (Figure 5)

Eutrophication in estuaries is usually caused by the loading of nutrients or organic matter from land (Ryther and Dunstan 1971; Cloern 2001). Organic loading stimulates estuarine eutrophication directly, and nutrient loading stimulates eutrophication by enhancing phytoplankton growth. Although the cause of eutrophication is straightforward, reducing it has proved difficult, and several long-term trends suggest that this problem will get worse (Diaz 2001). In developed countries

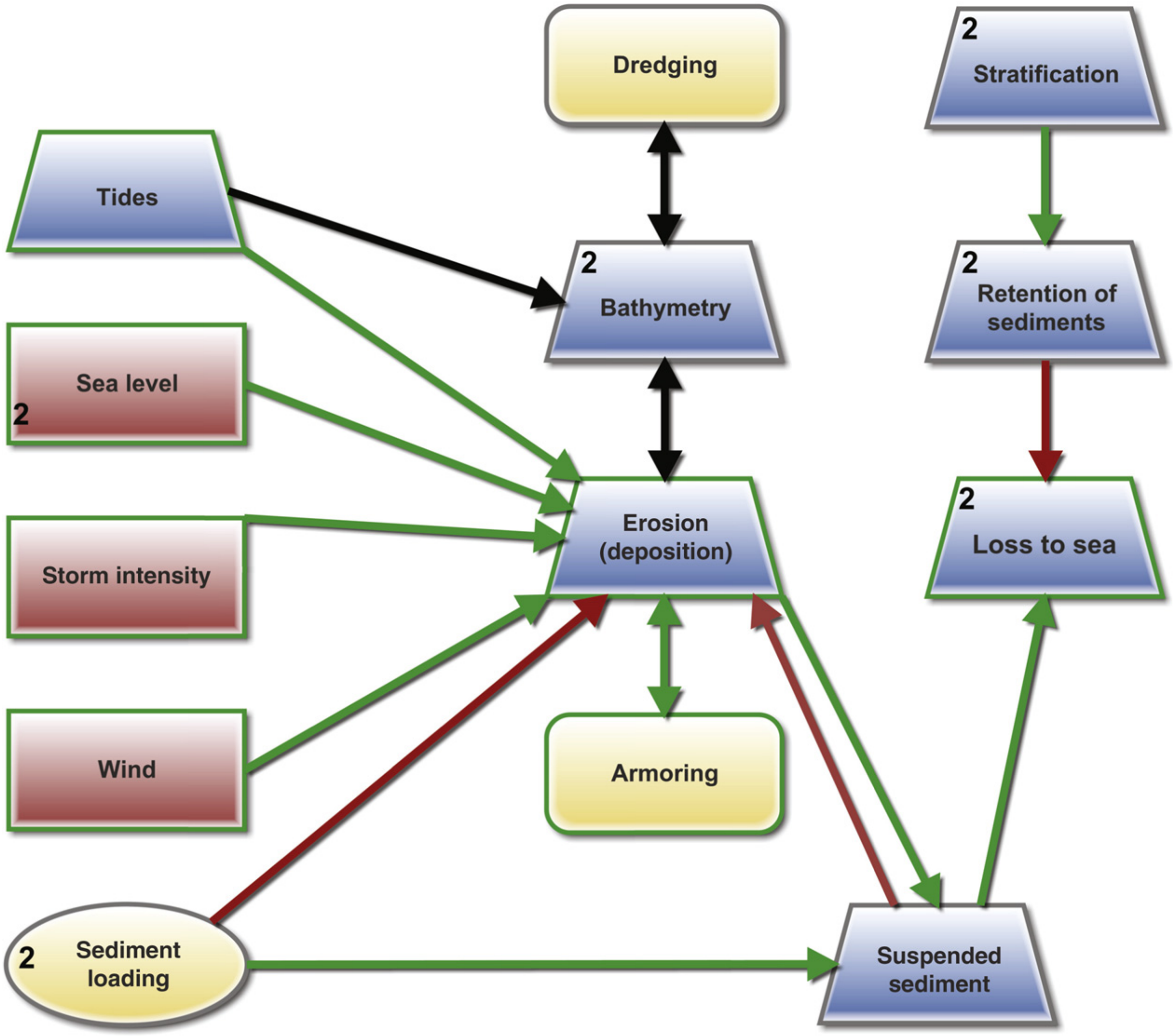

Figure 3 Schematic of the effects of changes in 'sediment supply, transport, and loss' on sediment deposition and erosion within an estuary, as described in Section 4.22.4.2.2 Sediment Supply, Transport, and Loss. Boxes, arrows, and numbers are as in **Figures 1 and 2**. Green is positive for erosion and negative for deposition. Red is negative for erosion and positive for deposition.

nutrient reductions achieved through improved treatment have been be offset by intensification of loading from non-point sources such as farms (Kemp et al. 2005).

Long residence time allows for production and decomposition of organic matter, and persistent stratification increases local residence time for sinking particles (see Section 4.22.2.1.2. Freshwater, Salinity, and Mixing), whereas turbidity caused by suspended sediment inhibits primary production. Therefore, either increases or decreases in freshwater flow could exacerbate eutrophication in estuaries, as could a reduction in turbidity because of decreases in suspended sediment.

Hypoxia is a persistent problem in many estuaries and coastal regions (Diaz and Rosenberg 1995; Diaz 2001; Conley et al. 2009), particularly in places in which eutrophication combines with restricted circulation such as in stratified, deep basins. Few benthic organisms can survive extended periods of hypoxia, and the hypoxic region is excluded as productive habitat (Breitburg 1992; Diaz and Rosenberg 1995). Increasing temperature raises microbial metabolic rates and can increase the frequency or extent of hypoxia.

The frequency of harmful algal blooms may be increasing worldwide, partly owing to high nutrient concentrations and high temperature (Anderson et al. 2002; Paerl and Huisman 2008). These blooms can reduce production of fish and other valued estuarine biota.

Increases in contaminant loading are also likely; for example, from urban runoff and intensified agricultural production. We do not consider contaminants further because their effects are often site-specific and sporadic.

4.22.4.2.5 Species Shifts (Figure 6)

Changes in range or phenology caused by regional warming, competition with introduced species, or other trends can increase or decrease the abundance of a species in an estuary and allow for colonization from other estuaries. To colonize an estuary, a founding population must survive transport from

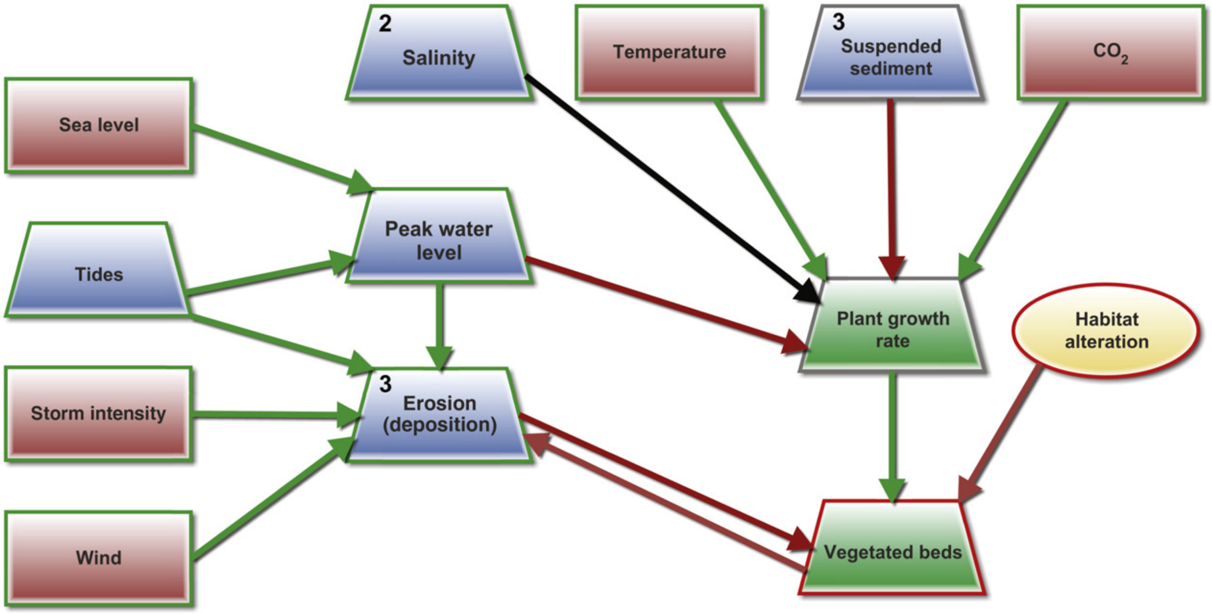
2
Salinity
Temperature
3
Suspended sediment
CO_2
Sea level
Peak water level
Tides
Plant growth rate
Habitat alteration
Storm intensity
3
Erosion (deposition)
Wind
Vegetated beds

Figure 4 Schematic relating climate, and other long-term, changes to the stability of 'vegetated beds' in estuaries, such as marshes, mangrove forests, and seagrass beds, as described in Section 4.22.4.2.3. Boxes, arrows, and numbers are as in **Figures 1–3** plus red borders indicate a likely negative trend.

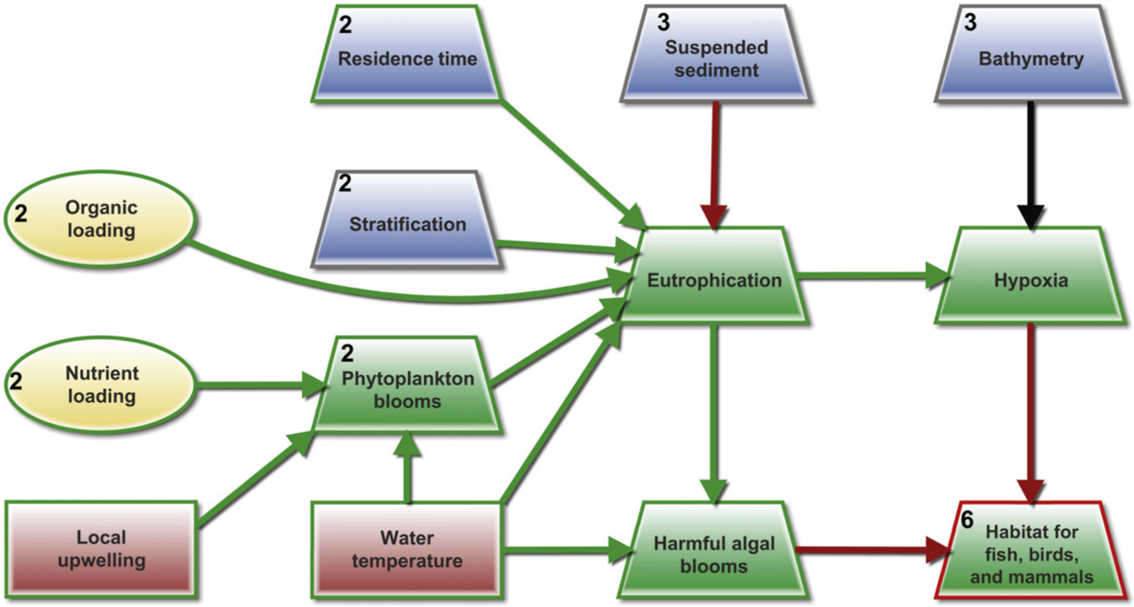
2
Residence time
3
Suspended sediment
3
Bathymetry
2
Organic loading
2
Stratification
Eutrophication
Hypoxia
2
Nutrient loading
2
Phytoplankton blooms
Local upwelling
Water temperature
Harmful algal blooms
6
Habitat for fish, birds, and mammals

Figure 5 Schematic relating climate, and other long-term, changes to 'eutrophication' in estuaries, as described in Section 4.22.4.2.4 Eutrophication. Boxes, arrows, and numbers are as in **Figures 1–3**.

one estuary to another, so colonization may be more frequent where estuaries are large, close, and hydrologically linked, as in the southeast United States. However, colonizers may be near the limit of their thermal tolerance. Species introduced artificially from another estuary of similar climate (e.g., Cordell et al. 2008) are more likely to find favorable conditions and quickly integrate into their new environment than natural colonizers (Cordell et al. 2008). Introductions are likely to remain the major mechanism for colonization in many estuaries, and are also likely to accelerate colonizations that would eventually occur through range shifts.

Successful colonization depends on environmental conditions such as suitable temperature, salinity, sediment type, flow conditions, and residence time. Interactions with local species are equally important (e.g., food supply, predators, shelter from predation, harvest). These physical and biological attributes are difficult to assess even in well-studied situations because of the myriad and often subtle species interactions

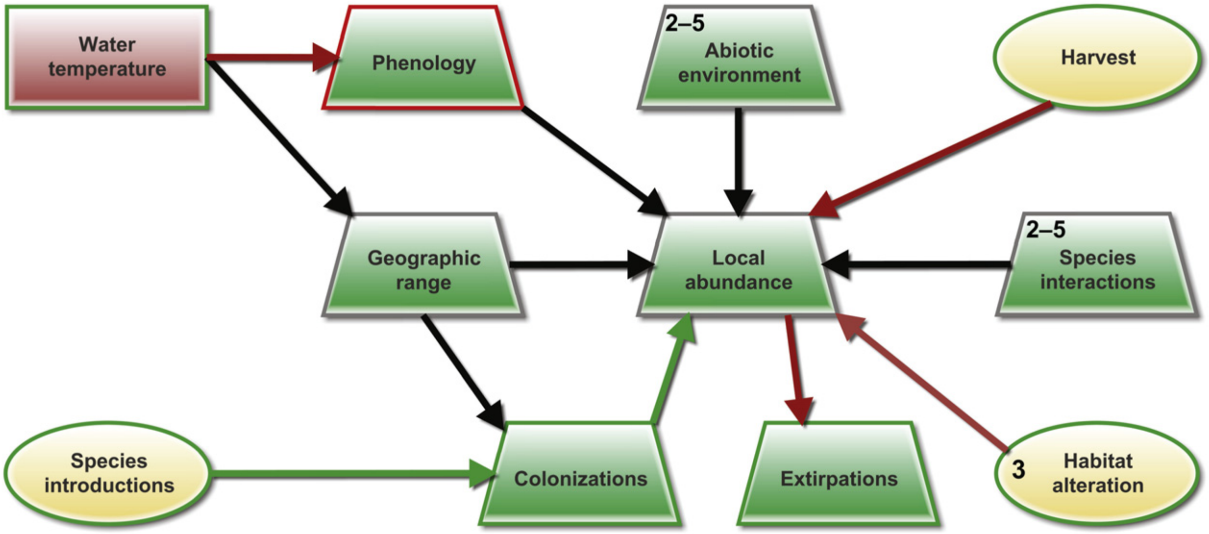

Figure 6 Schematic relating climate, and other long-term, changes to shifts in 'species composition' within estuaries, as described in Section 4.22.4.2.5. Boxes, arrows, and numbers are as in **Figures 1–4**. Except for the 'species interactions' box, this diagram refers to a single species in a single estuary.

such as concurrent shifts in range and phenology of predator and prey. For example, relative changes in phenology between a copepod and its gelatinous predator in Narragansett Bay, apparently caused by warming, have intensified the predator–prey relationship, resulting in seasonal extirpation of the copepod (Costello et al. 2006). Intertidal mussels on a rocky shore could withstand increasing temperature only in the absence of predators (Harley 2011). Thus, the 'species interaction' box in Figure 6 hides a tangle of interactions.

The potential also exists for long-distance effects of changes in species abundance. For example, some ducks and shorebirds migrate thousands of kilometers between summer and winter habitats. Some of these species are important components of estuarine ecosystems (e.g., Poulton et al. 2002), and changes in their abundance caused by events in their alternate habitat would affect those ecosystems.

4.22.4.3 Catastrophes

Although catastrophic events such as earthquakes and floods are inherently unpredictable, often their cumulative probability over decades can be calculated. Mount and Twiss (2005) estimated a two-thirds probability by 2050 of multiple failures among weakened levees in the California Delta, cutting off a water supply for about 23 million residents and about half of California's agriculture. This scenario is reminiscent of Hurricanes Katrina and Rita in the Gulf coast (Day et al. 2007) and the recent tsunamis in Indonesia (2010) and Japan (2011). The impact of catastrophes obviously depends on the particular characteristics of the estuary.

Catastrophic change may also occur when systems are pushed from one stable state into another. A slight change in salinity in a Danish fjord, caused by a decision to open a sluice gate to increase exchange with the ocean, transformed the estuary from a turbid state with high phytoplankton biomass to a clear state with numerous benthic filter-feeders (Petersen et al. 2008). Although examples of such apparently reversible state changes are uncommon, similar but irreversible state changes can accompany changes such as the spread of invasive species (see Section 4.22.4.2.5. Species Shifts (Figure 6)).

4.22.4.4 Application to Particular Estuaries

Here we describe anticipated responses to long-term change of three disparate estuaries. The San Francisco, Chesapeake, and Murray–Darling estuaries are large and intensely studied, with recent published reports on observed and predicted long-term change. Each has prominent intergovernmental agencies responsible for stewardship (e.g., the California Delta Stewardship Council, the Chesapeake Bay Program, and the Murray–Darling Basin Authority).

4.22.4.4.1 San Francisco Estuary

The major concerns for the SFE focus on the tidal freshwater region, a key element of California's water supply system, and the conflict between water supply and freshwater flow into the estuary. Impediments to solving this conflict in the long term include the historical loss of most of the fringing marshes to development, the prevalence of nonnative invasive species, the variable flow regime with a trend to earlier spring runoff peaks, and the seismic vulnerability of levees protecting subsided farmlands.

The SFE, which includes San Francisco Bay and the California Delta, is one of the largest and most-studied estuaries in North America. The SFE is a heavily urbanized estuary with a strongly agricultural watershed. Most of the freshwater for the estuary originates as snowmelt in the Sierra Nevada and flows through the Delta of the Sacramento and San Joaquin Rivers. The climate is Mediterranean, with a long summer dry season and a winter wet season with up to ninefold variation in annual runoff. Much of the annual flow is trapped behind dams for use through the dry season, and the lower reaches of the watershed are laced with canals and diversions. The intensive use of the watershed, coupled with interannual variability in seasonal water supply, is the main reason for the intense conflict over water in California.

A recent synthesis of information from an interdisciplinary modeling effort projected the effects of climate change on the SFE and its watershed through the twenty-first century (Cloern et al. 2011). Forecasts were based on two IPCC scenarios, one of moderate warming (PCM-B1) and the other of rapid warming and a decrease in precipitation (GFDL-A2), compared to a baseline period of 1970–1999. Cloern et al. (2011) used a series of models to estimate regional air and water temperature, precipitation, runoff, operation of the water storage and delivery system, sea level, and estuarine salinity and temperature. The forecasted changes were placed in the context of a system that has been radically altered by human activities.

Results for the A2 scenario showed a 0.4 °C/decade increase in regional air temperature, a 28-mm/decade decrease in precipitation, and a 12-cm/decade increase in sea level (see Cloern et al. 2011 for confidence limits). Estimated runoff if there were no dams or diversions ('unimpaired' runoff) decreased by 2%/decade, and the percent of runoff from snowmelt decreased by 1%/decade. Temperature in the Delta increased by 0.3 °C/decade and estuary-wide mean salinity by 0.5/decade (practical salinity scale). The cooler, wetter B1 scenario forecasted similar patterns but with smaller magnitude for most variables, and the changes in precipitation and runoff were not distinguishable from zero.

Increases in extremes were also predicted, including high water level leading to flooding, and high temperature in the Delta, imposing thermal stress on the endangered delta smelt *Hypomesus transpacificus*. The frequency of floods in the lower watershed will decrease, to the detriment of estuarine fishes that spawn or rear on floodplains such as the native Sacramento splittail *Pogonichthys macrolepidotus*.

Broader conclusions were that the Delta would become warmer, clearer, and more saline. These trends would reduce the sustainability of delta smelt, which is sensitive to high temperature, avoids high salinity, and is most abundant in turbid water (Feyrer et al. 2011).

Restoration activities are being planned and conducted with little consideration of anticipated changes in hydrology, temperature, and sediment supply, which may limit the feasibility of achieving restoration goals. Depletion of groundwater in the SFE's watershed (Famiglietti et al. 2011) indicates that California's water budget is oversubscribed. Changes in precipitation and seasonal runoff, together with the increased frequency of extreme flows, will complicate the water supply picture and aggravate the ongoing conflicts over water.

Cloern et al. (2011) explicitly left out consideration of human activities that might change the outcomes of the model scenarios, as well as potential impacts on marshes and on the seaward, more saline reaches of the estuary. California's water supply system could adapt to much of the change in flow timing and quantity while maintaining at least some flows for environmental conservation (Medellin-Azuara et al. 2008). The strong seasonal pattern in precipitation is the primary driver of seasonal and decadal variability in flow, whereas dams and diversions have mainly affected long-term trends (Enright and Culberson 2010). However, substantial alterations in the structure and operation of California's water supply system are being planned, notably a massive water diversion system to alleviate problems with pumping water from the tidal freshwater part of the system (Lund et al. 2007). The effect on estuarine salinity will depend on design of this system and its operating rules. Multiple seismically driven levee failures (Mount and Twiss 2005) would cause a large, immediate influx of saline water. Forecasts of salinity distributions based on climate change alone seem incomplete.

Most of the environmental problems of the SFE have been either caused by, or solutions are impeded by, introduced species (Nichols et al. 1990; Brown and Michniuk 2007; Lund et al. 2007). Introduction of additional, influential species such as the quagga mussel are likely, further compounding the uncertainty of climate projections.

A projection of extent and frequency of inundation of land showed large areas at risk, and predicted that the 100-year flood of year 2000 would be a 1-year event by mid-century (Knowles 2010). A review by Parker et al. (2011) addressed effects of climate change on tidal marshes, emphasizing sea-level rise as well as temperature and salinity. Rising sea level will cause loss of marsh area because the present-day sediment supply is inadequate to support accretion of marshes (Knowles 2010) and hard structures limit upland development of many marshes. Rising temperature and salinity are forecasted to cause physiological stress and reduce diversity of marshes (Parker et al. 2011). This review does not consider the likely decrease in sediment supply caused by trapping behind dams (Schoellhamer 2011) or in flooded islands (Mount and Twiss 2005).

4.22.4.4.2 Chesapeake Bay

Much of the concern for management in the Chesapeake Bay has focused on eutrophication and its influence on or interaction with hypoxia, loss of seagrass, and loss of oyster reefs (Breitburg 1992; Kemp et al. 2005). Non-point source inputs of nutrients have slowed the reduction of nutrient loading achieved through improved wastewater treatment (Kemp et al. 2005).

A recent review by Najjar et al. (2010) summarized the likely interactive impacts of end-of-century increases in temperature (2–6 °C), sea level (0.7–1.6 m), and precipitation on living resources, particularly eelgrass, fish, and shellfish. The general projection is for a continued trajectory toward a plankton-dominated, eutrophic system. Precipitation in the basin is expected to increase, particularly in winter–spring, with an increase in the frequency of high-rainfall events. The change in seasonal pattern of precipitation, together with increasing evapotranspiration in the watershed due to higher temperature, will sharpen the seasonal difference between high winter flows and low summer flows. Sea-level rise will increase salinity penetration into the Bay and increase the tidal range, resulting in stronger vertical mixing. In the brackish northern part of the Bay this tendency will be offset by higher spring flows, likely resulting in stronger and more persistent spring–summer stratification. The combination of stronger tidal currents and greater sediment loading owing to erosion in the watershed and extreme winter flows will likely result in more suspended sediment in the water column, although the interactions among factors affecting sediment make quantitative predictions difficult.

Loading of nutrients and organic matter from nonpoint systems will increase. Increased temperature and nutrient loading will cause spring diatom blooms to begin earlier and produce more biomass, allowing an earlier start to summer hypoxia. This tendency will be strengthened and extended by the increased strength of stratification. In addition, because respiration increases more steeply than photosynthesis with increasing temperature, the estuary may shift toward net heterotrophy and possibly lower foodweb efficiency and an increase in blooms of harmful algae.

Growth rates of vascular plants including submerged aquatic vegetation (SAV) and marsh vegetation will likely increase with increasing CO_2. Yet the geographic coverage of eelgrass and other SAV will likely continue to decline with increasing turbidity because of high phytoplankton biomass. In addition, eelgrass, at the southern limit of its range in the Chesapeake Bay, will likely suffer more overgrowth by epiphytes and diebacks due to warming. An increase in the duration of low-flow periods during droughts could increase water clarity and possibly benefit SAV. However, wetlands may be unable to keep up with the rate of sea-level rise through accretion of sediments.

Harvested species of fish and shellfish are subject to several long-term influences. In particular, habitat for fish and some shellfish will shrink as the extent of hypoxia grows (Breitburg 1992). Loss of oysters to overharvesting and disease may have shifted the entire system into a more eutrophic stable state (Kemp et al. 2005). Similarly, loss of seagrasses owing mainly to shading by phytoplankton has resulted in an alternative stable state, reversible only through a reduction of phytoplankton blooms (Kemp et al. 2005). Nonlinear interactions within this complex ecosystem, and the likelihood of range extensions into the Chesapeake Bay by potentially influential species, preclude confident predictions about future trajectories.

4.22.4.4.3 Murray–Darling System, Australia

The Murray–Darling river–estuary system illustrates the effects of long-term change in arid areas (Kingsford et al. 2011). Apparently most of this trend is human-driven. A severe drought in southeastern Australia from 1997 through mid-2010 was followed by floods in 2010–11. Total precipitation in the basin is not expected to decrease with climate change (Sun et al. 2011), and similar droughts have occurred in the past (Roderick 2011). What is unprecedented is the low flow in the river; because of water withdrawals for irrigation, almost no freshwater flowed into the estuary during the last 4 years of the drought (Webster 2010).

The estuary comprises two broad, shallow lakes and a long, narrow lagoon (the Coorong) behind a barrier beach. Although not urbanized, it is a popular recreational site and an important habitat for migratory waterbirds. Barrages installed to guide river flow to the mouth also restrict flows among the basins. The barrier island and river mouth are in a continual state of flux, exacerbated by the barrages (Bourman et al. 2000).

Toward the end of the drought the southern Coorong was intensely hypersaline because of high evaporation and sluggish exchange. The salinity of greater than 100 mg/l exceeded the tolerance of nearly all estuarine and marine organisms (Webster 2010). Lowered water levels exposed toxic sulfate soils and the Australian government spent ~A$1B on restoration without addressing the shortfall in flow (Kingsford et al. 2011). During subsequent floods the salinity has declined and valued species of fish and birds have returned to the Coorong.

Responses to the environmental problems in the Coorong were constrained by the near-total lack of freshwater above the minimum demanded for irrigation. Reallocation of the water supply is being considered (Roderick 2011; Kingsford et al. 2011), as is a pipe to connect the Coorong directly to the ocean (Webster 2010).

Thus, the Murray–Darling system illustrates how human uses of water can lead to severe degradation in an environmentally stressed estuary. This example also shows how local issues direct research; the emphasis in the relevant reports found on this system was on flows and barrages, with little mention of potential effects of warming, ocean acidification, or sea-level rise.

4.22.4.4.4 Summary of Case Studies

What is striking when comparing these three estuaries is the difference among the long-term processes dominant in each estuary: water supply and introduced species in the SFE, eutrophication in the Chesapeake Bay, and farming in an arid region in the Murray–Darling system. These estuaries are at about the same latitude, have temperate climates, and are in developed countries. The difference in emphasis is not caused by lack of information; in particular, the Chesapeake Bay and the SFE are perhaps the world's most-studied estuaries after the Baltic Sea. Rather, it reflects the prudent consideration of local conditions when researching and managing the effects of long-term change.

'Climate change' is a hot topic. Much less attention has been given to other long-term changes with similar magnitude and timescales (see Section 4.22.3.2 Direct Human Effects). All three studies presented here, particularly the Murray–Darling, emphasize the point made by Vörösmarty et al. (2000) more than a decade ago that local and regional human activity can dominate the trajectory of long-term change.

4.22.5 Implications for Ecosystem Functions and Services

Predicting the future of estuarine functions and services is difficult. First, projections of the state of natural–human systems over decades and longer are uncertain. Second, unforeseen changes in policy, technology, economics, and society will affect how estuarine services are used and managed. Third, each estuary is unique, as is its response to change. Fourth, our understanding of climate, other human influences, and ecosystem functions will improve along with efforts to mitigate and adapt.

Despite the uncertainty, some long-term influences have predictable trends with known risks that are likely to occur in many estuaries (see Sections 4.22.3.1 and 4.22.3.2, Table 2). These influences include temperature, sea level, ocean acidification, human population growth, habitat alteration, and introduced species. Rising temperature affects estuarine functions through physiological and phenomenological changes and range shifts, and through effects on river flow. Rising sea level increases erosion and degrades vegetated beds, shorelines, and structures. Ocean acidification reduces growth rates of oysters and mussels. Population growth increases the demand for water and other estuarine services. Increased demand for water reduces freshwater flow into estuaries. Habitat alterations eliminate vegetated beds and thereby diminish estuarine services such as disturbance regulation and food production. Introduced species alter community composition and biotic interactions but with less predictable consequences. All of these proximate impacts are likely to occur or are occurring in many estuaries, but outcomes for a particular estuary are less certain.

We have identified and diagrammed five mechanisms (see Section 4.22.4.2, **Table 1**, **Figures 2–6**) by which long-term influences amend estuarine functions and thereby degrade estuarine services in many estuaries: changes in freshwater flow, supply and loss of sediment, alteration of vegetated beds, eutrophication, and shifts in species. Each of these mechanisms applies to many estuaries, and the mechanisms can be used to deduce the likely long-term trajectory of an individual estuary.

Globally the supply of water falls short of human demand, and in most estuaries freshwater inflow will likely decrease. The joint effects of increased demand and reduced supply due to reduced precipitation and warming in the watershed (4.22.4.2.1) will exacerbate shortages and increase conflict in many if not most estuaries. Loss of inflow can lead to the collapse of functions and the complete loss of services, although the Murray–Darling system showed remarkable resilience following a decade-long lack of flow (see Section 4.22.4.2.).

The amount of available sediment in estuaries will decline globally as a result of sea-level rise, erosion, and damming and reduction in flood flows. The resulting reorganization of bathymetry and loss of shoreline and marsh habitats will impair estuarine services, particularly those provided by marshes and vegetated beds (**Table 1**). Reductions in turbidity will increase risk of eutrophication and alter predator–prey relationships. A decline in turbidity over the past three decades in the SFE is associated with declines in the endangered delta smelt (see Section 4.22.4.4.1.).

Habitat alteration for urban, agricultural, and other uses also eliminates ecosystem services provided by vegetated beds. Globally these habitats continue to decline. The interaction of habitat alteration with increased erosion resulting from sea-level rise, loss of sediment, and reductions in freshwater inflow leads to a continuing loss of these estuarine services. These losses are particularly apparent in south Asia, where removal of mangrove forests for aquaculture has resulted in losses of services such as shoreline protection and nursery habitats (Polidoro et al. 2010).

In eutrophic estuaries, ecosystem services are already under threat because of habitat degradation through shading of seagrass beds and development of harmful algal blooms and hypoxia, with attendant loss of benthic assemblages and habitat for higher trophic levels (see Section 4.22.4.2.4.). The principal long-term drivers of eutrophication are nutrient and organic loading, but stratification and therefore freshwater runoff are important factors, and temperature, habitat alteration, and turbidity contribute. Eutrophication can impair all of the ecosystem services listed in **Table 1**. For example, the loss of seagrass beds in the Chesapeake Bay, owing partly to eutrophication, eliminated physical habitat and a significant food resource for many harvested bay and coastal species.

Species distributions globally are moving poleward in response to warming, and flora and fauna are becoming homogenized through introductions. Species gains and losses will likewise continue in most estuaries through some combination of range shifts and introductions (see Section 4.22.4.2.5.). Overharvest may accelerate changes through alteration of trophic structure and removal of predators and competitors of potential colonizers. Further extirpations and even extinctions are likely.

General patterns and mechanisms of estuarine responses to changes in climate and other influences, such as those discussed in the preceding and in Section 4.22.4, can be used to establish a suite of tools (**Figures 2–6**) and concepts that researchers, managers, and policy makers can draw on in characterizing the attributes, mechanisms, and likely responses of a specific estuary and in designing management actions that will be effective in the long term. Widespread or general trends and mechanisms such as those summarized herein can be used as a starting point, provided the existing state of the estuary and the current stresses it faces are understood, and the parallel roles of climate and local human actions are considered.

The site-specific character of many of the responses to long-term change could be used to advantage. Local action will be needed to address the consequences of the global failure to act. Many governments and populations around estuaries have established sophisticated arrangements for stewardship and adaptation. These arrangements have led to increases not only in protection and restoration, but also in monitoring and research to understand these valued estuarine services, as well as public knowledge and understanding of the repercussions of long-term changes. These trends will help in understanding, mitigating, and adapting locally to the anticipated global loss of estuarine services.

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4.23 Vulnerability and Adaptation to Climate Change in the Canadian Arctic

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4.23.1 Introduction

Climate change is already being experienced in the Arctic, with implications for ecosystems and the human communities that depend on them (ACIA 2005; Huntington et al. 2007; IPCC 2007b; Furgal and Prowse 2008). Temperatures in the Arctic have been increasing at twice the global average (IPCC 2007a; Manabe et al. 2011), recent years have witnessed an unprecedented reduction in summer sea ice cover, permafrost is melting in some regions (Post et al. 2009), and extreme weather conditions have been described as being more unpredictable and frequent (IPCC 2007b). Indigenous peoples throughout the Circumpolar North have a profound interdependence with the natural environment, and many are already experiencing threats to their livelihoods – and lives – from the effects of climate change.

In Canada, the majority of the Inuit population lives in small, remote, coastal communities, and continues to depend on the harvesting of fish and wildlife for food security, income, and cultural well-being (AHDR 2004; Nuttall et al. 2005). This high dependence on the environment has made Inuit particularly susceptible to climate change, which is experienced together with socioeconomic, political, and cultural transformations (Anisimov et al. 2007; Lemmen et al. 2008). Compromised food security and health status, loss of life and serious injury, constrained transportation access and travel routes to hunting areas, and inability to practice traditional cultural activities have been documented across the Arctic, with the possibility of continued change into the foreseeable future with further effects on Inuit livelihoods (Furgal and Prowse 2008; Holland et al. 2010).

Research on climate change in the Arctic has provided considerable information about the implications of climate change for physical and biological systems. More recently there has been interest in the implications of climate change for northern people, their livelihoods, and their capacity to deal with and adapt to changing conditions. To understand how climate change is likely to affect people and communities requires knowledge of how people experience and respond to changing conditions, including the role of nonclimate factors (e.g., local economy, sociopolitical, cultural) (Duerden 2004; Ford and Smit 2004; McCarthy and Martello 2005). Studies adopting this perspective have been undertaken in Arctic communities from Alaska and Canada, Greenland and Iceland, as well as Norway, Finland, Sweden, and Russia (Hovelsrud and Smit 2010).

This chapter summarizes findings about the vulnerability and adaptation of arctic communities in the face of changing climatic conditions, with a focus on Inuit communities in Canada. The chapter first provides a brief overview of climate change and impacts in the Arctic, and outlines the evolution of analytical approaches to assessing vulnerability, noting the main features of the framework on which most of the community studies were based. Key vulnerabilities evident in the communities are then described, with detailed examples drawn from selected Canadian case studies. The chapter concludes with an assessment of the prospects for arctic communities to adapt to ongoing changes in climate-related conditions.

4.23.2 Climate Change Impacts in the Arctic

Climate change scenarios indicate that by the 2020s annual mean temperatures in the Arctic could increase in the order of 2 °C, with the greatest increases projected to occur during winter. Precipitation is expected to increase by up to 8% (IPCC 2007a). As with conditions already experienced, these changes will vary from one region to another (Furgal and Prowse 2008). Nonetheless, some broad impacts of climate change are projected, particularly in the cryosphere, which is crucial to ecosystem dynamics in arctic regions and is sensitive to changing climate.

Sea ice, a major component of the cryosphere, has already demonstrated significant responses to warmer climate. Arctic sea ice extent at the end of the melt season in September has declined sharply over the past decade and this trend is expected to accelerate in the future as a result of warming temperatures,

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hastening the ongoing transition toward a seasonally ice-free Arctic ocean (Stroeve et al. 2008). Moreover, ice cover is increasingly dominated by thin, first-year ice (ice formed during the previous autumn and winter) that is susceptible to melting out in summer. Thin ice is also more vulnerable to strong winds and anomalous summer temperatures. It is believed that warming of the Arctic has reduced the likelihood of cold years that could bring about temporary recovery of the ice cover (Stroeve et al. 2012).

Snow cover plays an important role in the climate, hydrological, and ecological systems of the Arctic and other regions. Snow cover affects the surface energy balance (e.g., reflectivity), water balance (e.g., water storage and release), thermal regimes (e.g., insulation), and vegetation and trace gas fluxes (Callaghan et al. 2011). Research has also demonstrated the importance of snow cover to nutrient cycles (Sullivan et al. 2008) and carbon budgets in the Arctic (Welker et al. 2000). Snow cover is decreasing in most regions of the Arctic, especially in spring, in response to warming temperatures (Kundzewicz et al. 2007).

Glaciers and Ice Sheets are also part of the cryosphere–hydrosphere, and changes in them affect the magnitude and timing of river flows and sea level. A large number of Canada's glaciers and ice caps are located in Arctic and Subarctic regions. Significant retreats have been documented in glacier fronts and volume since 1920 (Furgal and Prowse 2008).

Permafrost or frozen ground is the norm throughout most of the Arctic, and it too plays an important role in northern hydrology and ecosystems. There is evidence of widespread permafrost warming and degradation, reflected in increased summer thaw penetration, expansion of the active (freeze–thaw) layer, and contraction of the area of permafrost (Burn and Kokelj 2009; Post et al. 2009). These trends are expected to continue with climate change, evident in degradation of continuous to discontinuous permafrost, and the disappearance of discontinuous permafrost in the southern zones (Zhang et al. 2008). The thawing of permafrost is expected to release large pools of carbon, a feedback to the climate system (Schuur and Abbott 2011).

Rivers and Lakes are expected to have a shortened ice season and thinner ice cover in the winter. Changes in glaciers, permafrost, and snow and ice dynamics will all affect the hydrologic system, with implications for freshwater discharge and flow regimes (Kundzewisz et al. 2007).

Coasts represent the zone of interaction between marine and terrestrial physical and biological systems and the zone where human occupancy is concentrated. Projected rises in sea level are expected to affect Arctic coastlines, notably through flooding and erosion. In some areas, effects of sea level rise are moderated by isostatic rebound, whereas in other areas rising sea levels are exacerbated by coastal subsidence. Coastal erosion can be affected by sea level rise, and it is accentuated by permafrost degradation, reduction in the extent of sea ice cover, and changes in the frequency and severity of storms (Lantuit and Pollard 2008; Overeem et al. 2011).

Ecosystems respond to changes in the physical environment. It was expected, and has been documented, that with a warming climate, most eco-zones or species distributions have and will continue to gradually migrate northward, where there is the land or water needed by the species (Soja et al. 2007; Bellard et al. 2012). The adaptability of species to changes in ecosystem functions will vary among species, with some better able to adapt than others. Muskox and caribou (woodland and barren ground), for example, are sensitive to changes in forage and to the changes in the intensity of insect harassment, both of which affect feeding, animal condition, and subsequent reproduction and recruitment.

In the marine ecosystems, seals, walrus, narwhal, beluga, and polar bear are widely found throughout the Canadian Arctic and are commonly harvested by Inuit. Species, such as seals, dependent on sea ice as a platform for resting, pupping, molting, and feeding are already showing stress in their southern limit as ice conditions change. Earlier ice breakup and reductions in snow depth have affected ring seal survival and recruitment (Harwood et al. 2000; Loeng 2005). Species that rely on the ice-edge environment, such as beluga, narwhal, and walrus, are particularly vulnerable to the effects of projected decreases in sea ice cover (Loeng 2005).

The distribution of polar bears is largely a function of sea ice conditions that allow them to effectively hunt and reproduce. Ringed seals are an important food source for polar bears and hence the changes in ice conditions that affect ring seal populations directly affect polar bears. There is evidence of significant declines in the numbers and condition of polar bear populations in their southern range, notably in western Hudson Bay, and these trends are projected to continue (Stirling and Parkinson 2006; Hunter et al. 2010).

Inuit lives and livelihoods are closely dependent on these physical and biological systems. Inuit have identified changes in conditions that affect them and are already adapting to vulnerabilities associated with climate change.

4.23.3 Vulnerability and Adaptation

There is a strong international scientific consensus that climate change is already underway in the Arctic (ACIA 2005; IPCC 2007a). The main response of governments to concerns over climate change has been to seek reductions in greenhouse gas emissions to 'mitigate' changes to the climate system (UNFCCC 2002). While mitigation is clearly needed, even with the most aggressive control measures, current greenhouse gas emissions commit the Earth to some degree of climate change, requiring nations, regions, communities, and individuals to undergo some level of adaptation (Klein et al. 2005; Hare and Meinshausen 2006; Rogelj et al. 2010). Adaptation is particularly important in the Arctic where climate change is already affecting local ecosystems and livelihoods. Adaptation in the context of human dimensions of climate change refers to an adjustment in human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities (Smit et al. 1999). Adaptation is expected to address areas in which communities are vulnerable to climate change.

Several approaches have been employed to assess the implications of possible changes in climatic conditions in the Arctic and associated opportunities for adaptation. Research on climate impacts has been focusing on modeling future climate change scenarios, their physical effects, and the implications of hypothetical adaptations (IPCC 2001). Referred to as the 'climate impact approach' or the 'scenario-based approach,' these top–down studies have been conducted at large scales, and focused on long-term changes in average climate conditions (variables most readily available from climate models) for the main purpose of quantifying the net impact of climate change (Brooks 2003). Due to these limitations, a broader approach to adaptation needs to be adopted.

Adaptation, if addressed at all, has up to now focused on assuming the adoption of hypothetical technical measures (Klein et al. 1999). The climate impact approach has improved our understanding of the potential severity of future climate change impacts, but has not explicitly addressed adaptation processes (Jones and Boer 2003). Recognizing this deficiency in knowledge and understanding of adaptation, recent adaptation research has drawn on theory from social vulnerability (e.g., Sen 1981; Bohle et al. 1994; Adger 2003) and work in human ecology of natural hazards and risk management (e.g., Blaikie and Brookfield 1987; Blaikie et al. 1994; Cutter 1996), to develop an integrated understanding of vulnerability.

To initiate adaptation, decision makers need to know the nature of vulnerability, in terms of who and what (e.g., economy, food security, infrastructure, etc.) are vulnerable, to what stresses, and in what way, and also what is the capacity of the system to adapt to changing conditions (Smit et al. 2000; Turner et al. 2003; Schroter et al. 2005). In the climate change field, the term vulnerability refers to the susceptibility of a system (community) to harm relative to a climate stimulus or stimuli, and relates to the exposure-sensitivity of the community to a climate stimulus and the capacity to adapt (Smit and Wandel 2006). Beyond the climate change impact research, studies have built on the natural hazards field to focus on the social dimensions of human sensitivity and adaptability, and have considered vulnerability to climate change in the context of the other economic, social, cultural, and environmental forces that affect communities (Adger et al. 2001; Kasperson and Kasperson 2001; Cutter et al. 2003; Turner et al. 2003). It is also accepted that adaptation initiatives are most effective when they are integrated, or mainstreamed, into other resource management, disaster preparedness, and/or community planning programs and institutions (Burton et al. 2002; Ford et al. 2007; Huq et al. 2004; Klein et al. 2007). This integration requires active involvement and collaboration with community members, and knowledge of local institutions and policies and the forces that influence vulnerability. A research approach that captures these needs and is recognized by the ACIA (2005) and IPCC (2007b) is the 'vulnerability approach.'

The vulnerability approach seeks to describe the processes and forces that influence and structure vulnerabilities in particular places to help identify why vulnerability exists and to identify opportunities for adaptation (Smit et al. 2010). The approach first assesses current vulnerability by documenting how people are exposed and sensitive to climatic variables, and the adaptive strategies they employ to deal with these conditions. Then future vulnerability is estimated relative to current conditions and future climate possibilities and future social trends (Ford and Smit 2004). Exposure-sensitivity refers to the susceptibility of people and communities to variable conditions, and adaptive capacity refers to the potential of a community to adjust in order to deal with plausible changes (Smit and Wandel 2006). In order to document vulnerabilities, it is necessary to gain insights on the experiences of people and their livelihoods and institutions. As such, a key feature of this vulnerability approach is its engagement with the community as the first source of information, to identify the conditions that are pertinent to the community, and to document adaptive strategies actually employed. Hence this approach is sometimes called 'bottom–up' or 'starting point' in the climate change field.

4.23.4 The Canadian Arctic and Community Vulnerability Studies

The Canadian Arctic is divided into four Inuit regions as settled by comprehensive land claim agreements and together Inuit settlement regions cover 31% of the Canadian landmass (Table 1). There are approximately 50 000 Inuit living in the Canadian, with over half living in Nunavut and the other half dispersed across the other three settlement areas. The climate of the Canadian Arctic is characterized by seasonal extremes, cold, long winters and short, cool summers, with the majority of the land surface area composed of continuous permafrost. Sea ice is an important part of Inuit livelihoods and depending on the geographic location, the length of time that

Table 1 Selected characteristics of Inuit regions in the Canadian Arctic

Inuit region	*Province/Territory*	*Relevant land claim*	*Inuit population (% of total)*[a]	*Average individual total income ($)*[b]	*Unemployment rate*[b]	*Percent getting majority (>50%) of meat from traditional sources (%)*[c]
Inuvialuit settlement Region	Northwest territories	Inuvialuit Final Agreement (1984)	3115 (55%)	25 509	12.3	38
Nunavut	Nunavut	Nunavut Land Claim Agreement (1993)	24 635 (84%)	26 924	17.4	41
Nunavik	Quebec	James Bay and Northern Quebec Agreement (1975)	9565 (90%)	23 215	14.5	40
Nunatsiavut	Newfoundland & Labrador	Nunatsiavut Agreement (2005)	2169 (89%)	17 945	40.3	33

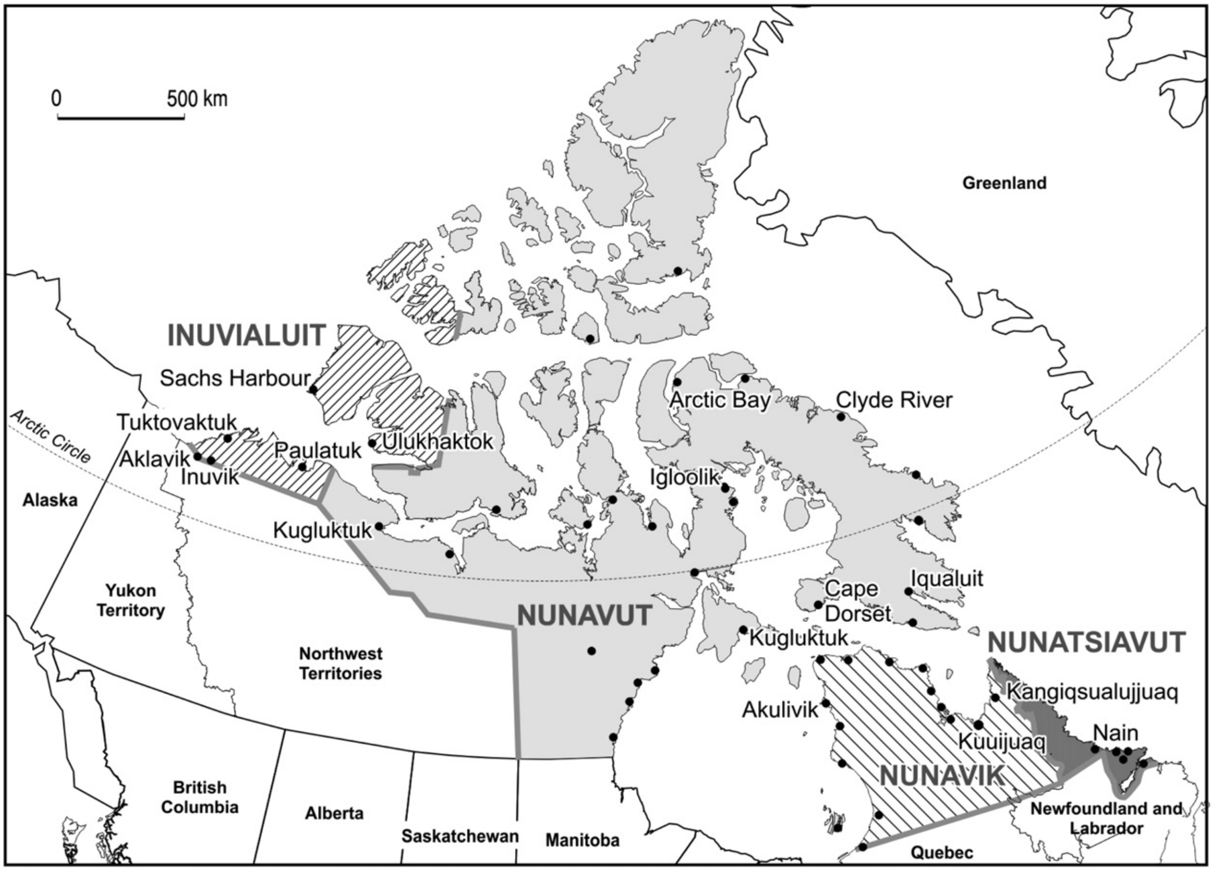
[a] *Statistics Canada (2006).*
[b] *Statistics Canada, 2001 Census of Population, INAC customized tabulations.*
[c] *Poppel et al. (2007).*

the ocean is frozen varies from approximately 7 months to nearly year-long coverage. Inuit use the sea ice for hunting marine wildlife and for traveling to hunting grounds and to other communities.

Most Inuit live in small, remote, coastal communities, with economies composed of wage employment and subsistence hunting. Prior to settling in communities, Inuit were semi-nomadic and traveled on the land, following wildlife and seasonal patterns. The wage economy in most arctic communities is based on public administration, arts and crafts, tourism, and increasingly on resource extraction. Despite undergoing sweeping political, social, and economic changes in the past half-century, subsistence hunting, fishing, and trapping continue to be important in the lives of many Inuit, and country foods (locally harvested fish and wildlife) are the main source of meat for many households. However, settlement in communities and associated changes have also stressed Inuit society and communities are challenged by limited access to health care services, low socioeconomic status, high unemployment, poor quality housing, concerns regarding basic services such as drinking water quality and sanitation, and low educational achievement (AHDR 2004; Furgal and Prowse 2008). It is within this context that Inuit communities experience and respond to climate, with socioeconomic and political conditions influencing how communities are affected by climate and their capacity to adapt.

Studies of Inuit perceptions of change and vulnerability to change have been undertaken in a range of communities across the Canadian Arctic (**Figure 1**). This chapter draws mainly on published community-based studies of vulnerability to climate change including Tuktoyaktuk, Ulukhaktok, Sachs Harbour, Inuvik, Aklavik, and Paulatuk in the Inuvialuit Settlement Region (ISR); Igloolik, Arctic Bay, Clyde River, Cape Dorset, Iqaluit, and Kugluktuk in Nunavut; Akulivik, Kangiqsualujjuaq, and Kuujjuaq in Nunavik; and Nain in Nunatsiavut (Berkes and Jolly 2002; Ford et al. 2006a, Ford et al. 2006b; Furgal and Sequin 2006; Gearheard et al. 2006; Tremblay et al. 2008; Ford and Beaumier 2010; Friendship and Community of Aklavik 2011; Pearce et al. 2010; Pearce et al. 2011; Prno et al. 2011; Andrachuk and Smit 2012; Pearce et al. 2012). Although the susceptibilities to changing conditions are distinct to each community, because both the exposure-sensitivities and adaptive strategies are place specific, there are some broad types of vulnerability that are evident across the Canadian Arctic (**Table 2**).

Each type of vulnerability represents an aspect of community susceptibility; however, they are not discrete, but rather are interrelated – for example conditions that influence hunting are also relevant to transportation, culture and learning, and health and well-being. In the following sections, each of these types of vulnerability is outlined, with illustrative examples from selected communities.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Kugluktuk
Arctic Bay
Clyde River
Igloolik
Yukon Territory
Cape Dorset
Iqualuit
NUNAVUT
Northwest Territories
Kugluktuk
NUNATSIAVUT
Akulivik
Kangiqsualujjuaq
Nain
Kuujjuaq
NUNAVIK
British Columbia
Alberta
Saskatchewan
Manitoba
Newfoundland and Labrador
Quebec

Figure 1 Canada's Inuit regions and communities (communities referred to in the chapter are named).

Table 2 Main types of vulnerability in Canadian Arctic communities

Vulnerability types	*Common elements*
Subsistence hunting	Increased travel risks; access to hunting grounds; quality and availability of wildlife
Transportation	Compromised trail routes to hunting grounds
Infrastructure	Permafrost degradation affecting buildings; coastal erosion
Health and well-being	Food security – access, availability, quality
Culture and learning	Erosion of environmental knowledge and land skills among young Inuit
Business and economy	New shipping opportunities; compromised ice roads; negative consequences for sport hunting industry (local guides and outfitter; local businesses)

4.23.5 Subsistence Hunting

Harvesting fish and wildlife for food and income is a long established and highly regarded feature of Inuit society. In the context of subsistence hunting, changes in temperature and seasonality, shifts in sea ice and wind dynamics, and weather patterns exacerbate risks associated with hunting and travel, and affect the health and availability of some species of wildlife important for subsistence. Traveling on the land, water, and sea ice is inherently dangerous and Inuit have long known about and coped with these risks. However, in recent years, changes in climatic conditions have altered, and in some cases increased, the magnitude and frequency of hazards with which people have to deal. In particular, hunters are increasingly exposed to hazards associated with more variable and less predictable weather: the weather changes quickly with minimal warning, and it is difficult to forecast wind direction and the development of storms. For example, Pearce et al. (2010) documented in Ulukhaktok, Northwest Territories (NWT), that less predictable weather, stronger winds, and severe storms are making travel and hunting more difficult, if not impossible, and increasingly hazardous. 'White-out' conditions reduce visibility and travelers have been separated from their travel patterns, lost, stranded, and have encountered hazards such as driving their snow machines into rocks or over cliffs, a hazard that would be avoided in better visibility. Hunters explain that they are unable to read signs in the weather like they used to because the weather and seasonal changes no longer follow regular patterns (Pearce et al. 2010).

In the marine environment, hunters are increasingly faced with risks associated with changing sea ice conditions. Some areas of sea ice, over which hunters are accustomed to travel, are no longer stable and in some instances the ice is not forming or does not form in a manner consistent with their experiences (Ford et al. 2006a,b; Pearce et al. 2010). Unstable ice conditions, together with greater variability and less predictable weather, are making it difficult for hunters to identify when it is safe to travel. There have been several cases of hunters being stranded and/or injured due to rapidly changing ice conditions, sometimes requiring assistance from federal search and rescue efforts. For example, in Igloolik, Nunavut sudden and rapid changes in the wind and consequently sea ice dynamics have stranded walrus hunters on moving pack ice, and resulted in the loss of hunting equipment (Ford et al. 2006a).

Inuit hunters are adapting to the enhanced risks associated with changing climatic conditions by taking extra precautions before and during travel. Hunters are taking extra time to read environmental signs and weather forecasts before traveling. This may include consulting elders and/or other experienced hunters to determine whether conditions are safe for travel and also satellite imagery of the sea ice and weather forecasts. Hunters are packing extra gas, heating fuel, food, and supplies in the event that they become stranded on the land. During times of the year when conditions are most precarious (e.g., late fall and early spring), some hunters are choosing to travel closer to the community and by established trail routes. Hunters are also more often traveling in groups, and are carrying VHF radios and satellite phones to maintain communication with people in the community. Some analyses of climate change impacts have suggested that the gradual retreat of sea ice extent would be a problem for Inuit hunters. Evidence on the ground indicates that hunters can readily adapt to such changes in ice extent (e.g., by not having to travel such long distances to the floe edge for hunting), but they are challenged more by changes in the stability of the ice over which they travel and by changes in the abundance, location, and condition of species they hunt.

Changes have been documented in the health and availability of some species of wildlife important for subsistence with possible links to climate change (Nancarrow and Chan 2010; Regehr et al. 2010). A study of the ringed seal population in the Beaufort Sea documented that even a very local, small-scale, premature disruption of the landfast breeding habitat has significant negative impacts on the growth, condition, and survival of unweaned pups (Harwood et al. 2000). Warmer temperatures in spring have caused seal birth lairs to melt earlier, exposing pups at earlier ages to predation and freeze–thaw cycles. As ringed seals are the primary prey of polar bears, a decline in ringed seal populations, especially in birth rate, is capable of having negative effects on the health of polar bears (Stirling and Parkinson 2006). Inuit across the Canadian Arctic hunt polar bear for subsistence and as a source of income. There are differing perspectives on the links between polar bear health and climate change most likely the result of climate change impacts being spatially uneven; some polar bear populations may be negatively affected by changing ice conditions, whereas other may not be. For example, scientists studying a population of polar bear in Hudson Bay have documented a significant positive relationship between the timing of sea ice breakup and the body condition of adult female polar bears (the earlier the ice breakup, the poorer the body condition of the bears) (Stirling et al. 1999, Stirling and Parkinson 2006). Later sea ice freeze-up and earlier breakup have also been linked to reduced reproductive rates in the same population of bears (Derocher et al. 2004).

Inuit have demonstrated strong adaptability to changes in the availability of wildlife species important for subsistence.

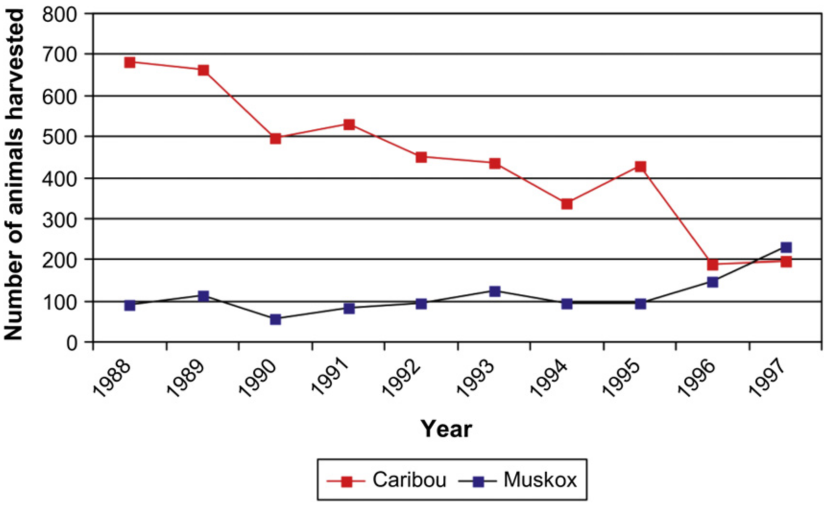

Figure 2 Number of caribou and muskox harvested by hunters in Ulukhaktok, Northwest Territories between the years 1988 and 1997. Source: IHS, 2003: *Inuvialuit Harvesters Study: Data and Methods Report, 1988–1997*. Inuvialuit Joint Secretariat. 202 pp.

When one species of wildlife is less abundant, Inuit shift to harvest another species of wildlife, an adaptation that has been possible due to the diversity of wildlife available in the Arctic environment. For example, beginning in the late 1970s, there was a dramatic decline in the Peary caribou population on the Arctic islands, a primary source of meat for many Inuit. A possible cause for this decline in caribou is the increase in freeze–thaw events, which has resulted in ice layers developing in the snow pack and hinders the ability of caribou to travel and forage for food (Russel 2007). In 1993, the community of Ulukhaktok implemented a voluntary moratorium on hunting Peary caribou and was able to supplement muskox for the lost caribou meat (Figure 2).

4.23.6 Transportation

Changing snow and ice regimes, less predictable weather, and changing wind patterns are increasing dangers for travelers, making semipermanent trails for hunting and recreational travel less dependable, and compromising the ability to engage in harvesting activities (Aporta and Higgs 2005; Ford et al. 2006a, 2006b; Tremblay et al. 2008; Pearce et al. 2010). Travel risks are especially pronounced during fall freeze-up, with warming and more variable temperatures prolonging the period of ice instability, and during spring melt, with less predictable snow and ice regimes.

The spring is a popular time for Inuit to travel on the land to ice fish at lakes and to hunt terrestrial wildlife (e.g., muskox, caribou), and on the sea ice to hunt marine wildlife (e.g., seals, whales, walrus, polar bear). However, in recent years changes in the timing and nature of the spring melt have resulted in earlier and more rapid melting of snow and ice, which has made travel by snow machine more difficult, dangerous, and sometimes impossible. An Inuit elder from Ulukhaktok, a small settlement located in the western Canadian Arctic, explained that in the years that he has been traveling on the land the spring melt usually started in May and June and the snow would melt gradually from the top down. In recent years, however, the melting has started from underneath the surface of the snow, and although snow conditions appear to be good for traveling, they are not because there is so much moisture and water under the snow that snow machines sink and become stuck in the moist ground (Pearce et al. 2010). Rapid periods of melting have also caused rivers and lakes to thaw earlier, which has affected travel routes and sometimes blocked travelers from being able to return to the community. These local observations and knowledge are consistent with instrumental measurements of the spring melt in the western Canadian Arctic. An increase in the number of days with thaw defined as a day with snow on the ground when the daily mean temperature is above $-2\,^{\circ}\mathrm{C}$ (Brown 2000) has been recorded over the past 50 years (Smith 1998; Callaghan et al. 2011).

Inuit are adapting to changing trail conditions by altering the timing and location of hunting activities, switching species harvested, using new travel routes, and avoiding travel at certain times and locations (Furgal and Seguin 2006, Gearheard et al. 2006, Ford et al. 2008, Tremblay et al. 2008). For example, in the event of an early sea ice breakup or late freeze-up (when travel on the sea ice is not feasible), hunters who have access to alternative modes of transportation have adapted by traveling to hunting areas by all-terrain vehicle (ATV) or boat. Several factors underpin these adaptive responses including, but not limited to, access to alternative modes of transportation, availability of alternative species of wildlife to hunt, and traditional knowledge and land skills, which enable hunters to travel in unfamiliar locations.

4.23.7 Infrastructure

Across the Arctic, thawing permafrost, changes in the coastal zone, and extreme weather events have damaged buildings, roadways, airports, and utilities (Instanes 2005). The sensitivity of built infrastructure (e.g., roads, buildings, utilities, airports), however, varies depending on the geography of the community. For example, communities located in the Mackenzie Delta in the western Canadian Arctic are particularly sensitive to permafrost thaw due to their construction on ice-rich flood plains (Hoeve et al. 2006). Coastal erosion, flooding, and warming in 'shoulder seasons' (i.e., fall freeze-up, spring melt) has also affected the integrity of buildings, services, and winter road networks.

The Inuvialuit settlement of Tuktoyaktuk provides an illustration of the vulnerability of infrastructure to climate change (Andrachuk and Smit 2012). Buildings and other infrastructure in Tuktoyaktuk are highly susceptible to damage due to permafrost degradation and coastal erosion. The mainland coast of the Beaufort Sea is characteristically prone to erosion, with average retreat rates in some areas of 1 m year^{-1} (Carmack and MacDonald 2002). The shorelines of the community itself are known to have eroded on average 1 to 2 m year^{-1}, but erosion of several meters has occurred during individual storms (Couture et al. 2002; Solomon et al. 1993). Climate change is generally considered to exacerbate shoreline erosion. It is thought that since sea ice provides protection for shorelines by suppressing the development of waves, longer open water seasons (and thus greater fetch distances for wave buildup) are enabling greater rates of erosion (Manson and Solomon 2007). The key conditions are high-energy storm events. Average daily energy acting upon shorelines has a relatively small impact on shorelines compared to strong storm events that can cause considerable change in relatively short periods of time, especially with winds blowing from the northwest, which leads to the most direct exposure. Such events of rapid coastal retreat tend to occur in late August and September in Tuktoyaktuk when strong storm events are more frequent. This is also the time when later freeze-up leaves the shorelines less protected by ice. Shoreline protection measures were initiated in the 1970s and have moderated shoreline erosion along parts of the coast; however, these efforts have not been successful in stopping all erosion, and it is questionable whether they will be able to withstand changes associated with some of the plausible changes in the region's climatic conditions.

4.23.8 Health and Well-Being

The effects of climate change on subsistence hunting have implications for Inuit food security, which concerns the ability of individuals and households to reliably access food of an acceptable quality. Three components of food security – access, availability, and quality – are particularly sensitive to climate change. In some instances, the connection between climate change and food security is direct. For example, as described in the previous section, changing sea ice conditions are affecting the ability of hunters to access hunting grounds. Furthermore, changes in the health and availability of some species of wildlife affect the success of hunts and the quality of some meat. In other instances, the link is indirect where food security is affected by the increased economic burden of hunting imposed by changing climate conditions. For example, if trails on the sea ice are unstable and hunters are required to travel by ATV or boat to access hunting grounds, only hunters with access to these modes of transportation are able to continue to hunt and this may result in some households acquiring less country food.

Inuit have historically responded to changes in access to country foods by distributing food through traditional sharing networks. Food sharing provides community members with country foods despite their ability to engage in subsistence, including those whose access to country foods is inhibited by changing climatic conditions. Food sharing is also part of a greater emotional and social bond that is built among individuals and which is important for a healthy community.

4.23.9 Culture and Learning

The ability of Inuit to adapt to climatic changes that affect subsistence hunting is influenced by the level of knowledge one has of the Arctic environment, which affords some Inuit dynamic and flexible use of the land and its resources. Traditionally, hunters managed risk by careful planning and preparation, bringing the right equipment, taking precautions, and by noting critical signs in the environment and responding appropriately. Knowledge of animal behavior enabled them to adapt to changing animal numbers and location, while knowledge of the land underpins the ability to do this. Traditionally, environmental knowledge and land skills were transmitted between generations through practical engagement with the environment. However, younger Inuit are spending considerably less time engaged in subsistence activities beyond organized land-camps and occasional hunting trips, but more time in formal education and wage employment. As a result, many younger and inexperienced hunters are not as well equipped to cope with the risks of hunting. More than a few young Inuit have encountered hazards and some have been seriously injured because of their poor understanding of dangers on the land. Changing climatic conditions are making it even more dangerous for them.

There is an expressed need among Inuit and northern educators for educational programming that supports the teaching and transmission of environmental knowledge and land skills in order to strengthen the competence of young Inuit, and therefore Inuit capacity to adapt to changing climatic conditions. Some communities are facilitating land-camps, led by elders and experienced hunters, to help engage youth who may otherwise not have the opportunity, in subsistence activities. In other cases, land skills such as navigation and wayfinding, and basic hunting and meat preparation skills are being taught in the school and applied during school-organized hunting trips. In Nunavut, an Inuit cultural school, Piqqusilirivvik, is being developed in Clyde River and is an attempt to integrate Inuit traditional modes of learning into a formal education setting. Initiatives to support the teaching of environmental knowledge and land skills, while not directed at climate change adaptation specifically, will indirectly prepare Inuit to deal with and adapt to climatic changes that affect subsistence.

4.23.10 Business and Economy

Most Inuit living in the Canadian Arctic live in small remote settlements that are accessible by air year round and by boat in the ice-free open water period of the summer. The economies of most communities are a mix of wage employment, administration, municipal services, arts and crafts, tourism, and subsistence. Climate change presents both risks and new opportunities for northern economies. Mining development is expanding rapidly in the Canadian Arctic, aided by reduced sea ice cover in summer months, which is improving shipping access and may continue to improve in the future (Stroeve et al. 2008). Changing sea ice regimes are also increasing opportunities for cruise-ship tourism, which presents potential income-generating opportunities for communities on the ship's path. However, climate change also presents a number of challenges for economic development in the north. For example, in the western Canadian Arctic, the viability of seasonal ice roads to diamond mining operations have been compromised due to warming winter temperatures and early spring melts (Pearce et al. 2010). The listing of polar bears as a 'vulnerable species' due to climate change under the U.S. Endangered Species Act in 2008, and subsequent ban on the importation of polar bear products to the United States, has also had negative economic consequences for Inuit communities, who once relied on American sport hunters for their income (Freeman and Wenzel 2006; Dowsley 2009).

4.23.11 Conclusions

Among the most compelling manifestations of climate change are those occurring in the Arctic: shrinking sea ice, melting permafrost, and threats to terrestrial and marine biota. Humans in the Arctic, notably the indigenous populations, are particularly dependent on the natural environment, and hence are vulnerable to climate-related changes in the cryosphere and hydrologic systems, and to shifts in animal populations. The human dimension of the Arctic ecosystem is experiencing the effects of a changing regional climate, and is adapting to these new conditions at the same time as it is dealing with a range of social, cultural, and economic pressures from outside.

Among the Inuit of the Canadian Arctic, notwithstanding differences from region-to-region and community-to-community, there are several commonly recurring vulnerabilities. Subsistence hunting is important for food, culture, and income, and is susceptible to changes in wildlife populations and access to hunting areas. Transportation is becoming problematic as trail routes are compromised by changes in the stability of ice. Permafrost degradation has implications for community infrastructure and for coastal erosion. Changes in the availability of harvested food contribute an additional risk to people's health. Also the erosion of environmental knowledge and land skills enhances the vulnerability of Inuit culture. Economic opportunities may come with more shipping, but may be constrained by closed ice roads and limits on the sport hunting industry.

Inuit pride themselves on their adaptability. They have had to adapt to some of the most severe environmental conditions known to humankind, and they have demonstrated considerable resilience in the face of changes already experienced. Given that climate change is expected to continue and accelerate, the question arises: how far and in what areas can the resilience of Inuit stretch? There are certainly opportunities to enhance the capacity to adapt to changing climate conditions, but this capacity clearly has some significant constraints. Constraints to Inuit adaptation include, but are not limited to, changing levels of traditional knowledge and skills among younger generation Inuit; high costs of hunting; limited financial resources (few wage jobs, lack of qualifications, nepotism); substance abuse (sapping material resources and impairing decision making); infrastructure not well-adapted to a changing climate; reduced resource-use flexibility due to harvesting seasons and quotas; and constraints due to the nature of some community locations (e.g., access to wildlife species; susceptibility of infrastructure to harm due to local geography – permafrost, coastal erosion). Constraints to adaptation, however, represent strategic policy entry points in which to enhance adaptive capacity now and in the future. Supporting efforts that increase financial, health, educational (e.g., supporting the teaching of environmental knowledge and land skills), institutional (e.g., flexible wildlife management regimes), and cultural capacity will inadvertently enhance the adaptive capacity of Inuit to deal with current and expected future climate change risks.

Photo 1: Taking extra precautions when traveling on the land and ice

Subject in photo: Roland Notaina and Joseph Kuptana, Ulukhaktok, Northwest Territories, Canada
Date: March 2009
Location: On the land near Ulukhaktok
Inuit hunters, Joseph Kuptana and Roland Notaina, secure supplies in their aalliaks (sled) during a hunting trip for omingmak (muskox). Hunters in Ulukhaktok are increasingly taking extra precautions when traveling, including traveling with extra fuel and supplies and carrying VHF radios and GPS, to avoid and/or be prepared to cope with emerging risks.

Photo 2: Changing sea ice conditions

Subject in photo: Adam Kolouhok Kudlak, Ulukhaktok, Northwest Territories, Canada
Date: 20 February 2009
Location: Open water lead (aolagot) near Holman Island (Qikiktakyoak)
Inuit travel on the sea ice to access hunting grounds. Arctic sea ice extent and volume, however, have been declining rapidly, compromising travel routes and creating new hazards for hunters.

Photo 3: Muskox

Subject in photo: Muskox
Date: March 2010
Location: On the land near Ulukhaktok.
Muskox are hunted by Inuit for their meat and hides, which are valued for their kiviut (wool). When there was a decline in the Peary caribou population, Inuit in Ulukhaktok switched to harvesting more muskox, demonstrating flexibility in harvesting techniques and dietary needs.

Photo 4: Tuktoyaktuk shoreline

Date: August 2007
Location: Tuktoyaktuk
Buildings and other infrastructure in Tuktoyaktuk are highly susceptible to damage due to permafrost degradation and coastal erosion.

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4.24 Vulnerability of the Ski Industry

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4.24.1 Introduction

Over the latter half of the twentieth century, tourism grew rapidly into a global economic and social phenomenon. Despite multiple economic, environmental, social, and political challenges and occasional major shocks – from recessions to terrorism to disease epidemics – the last six decades have seen extraordinary growth in international tourism, as well as domestic tourism in many nations. From 1950 to 2005, international arrivals increased by 6.5% per year, from an estimated 25 million in 1950 to 940 million in 2010 (United Nations World Tourism Organization (UNTWO) 2011). Tourism contributes directly to between 5 and 9.6% of the world's GDP and an estimated 8% of worldwide employment (World Travel and Tourism Council 2009). The next two decades are anticipated to see sustained growth in the tourism sector, though at a slightly slower pace than previous decades, with international leisure and business arrivals reaching 1.8×10^9 in 2030 and four times as many tourists traveling domestically (UNWTO 2011).

Tourism development has been and will continue to be influenced by many macro-scale factors, including economic growth, demographic change in industrialized and developing countries, increased travel safety and health concerns, social trends, environmental and cultural awareness, advances in communication and information technologies, environmental conditions (including climate), and transportation access and speed. It is important to recognize that specific tourism destinations and market segments are differentially sensitive to changes in and interactions between these macro-scale factors.

Tourism has been recognized as a highly climate sensitive sector since the 1970s (Maunder 1970; Perry 1972). A more recent World Meteorological Organization White Paper (Scott and Lemieux 2010) outlined the multifaceted and complex interface between weather, climate and tourists, tourism operators, and destinations. Weather and climate have broad significance to tourist decision-making and the travel experience. Climate, both at home and at a destination, is a salient motivator for many tourists and a key factor considered, either consciously or implicitly, in destination choice. Destination weather is an intrinsic component of the travel experience and has been shown to influence tourist activity choices and expenditures, as well as overall trip satisfaction.

Weather affects tourism operators in several ways (e.g., investment and locational analysis, infrastructure design, operational decisions and budgeting, risk assessment, and marketing) and over a wide range of timescales. Interannual weather variability defines the length and quality of multibillion dollar tourism seasons in different parts of the world. Extreme weather and climate-related environmental events also routinely have major impacts on tourism operators, particularly those located in highly dynamic environments like coastal areas, mountains, or fire-prone forests.

Weather and climate are also salient for tourism destinations, influencing their short- or long-term competitiveness and sustainability in diverse ways. All tourism destinations are affected either positively or negatively by natural seasonality in travel demand; interannual weather variability that can bring unseasonable temperatures or substantial fluctuations in precipitation causing drought, flooding, or transportation interruptions, and extreme events that not only affect tourist comfort and safety (and thereby satisfaction), but also the products that attract tourists and tourism infrastructure. Climate has universal importance in defining destination attractiveness and is used extensively in marketing, often with an obvious 'blue sky' bias.

The natural environment, personal safety, travel costs, and accessibility are the primary factors that affect travel decisions and the success of tourism. Because each of these factors can be highly impacted by regional climate and climate policy (Gössling and Hall 2006; Scott et al. 2008; Becken and Hay 2007), climate is considered a pivotal issue for medium and long-term future tourism development. Tourism is also considered to be one of the major global economic sectors that are currently the least prepared to deal with possible changes in climate (KPMG 2008).

Specific types of tourism destinations and market segments are differentially sensitive to climate and environmental change, with mountain destinations and winter sports tourism considered being particularly sensitive. After coasts and islands, mountains are considered the most important destinations for global tourism. Tourism is of great economic importance to many mountain communities and is one of the fastest-growing economic sectors for mountain regions of the world (Godde et al. 2000). Mountain ecosystems are among the most vulnerable to environmental change (Beniston 2000; Parry

http://dx.doi.org/10.1016/B978-0-12-384703-4.00440-8

et al. 2007), with possible retreat of alpine glaciers and changes in ecosystem composition and distribution potentially reshaping natural and cultural alpine landscapes in the decades ahead. A number of authors have warned of the potential negative effects of landscape change for mountain tourism (Wall 1992; Elsasser and Bürki 2002; Nyaupane and Chhetri 2009), though empirical analysis of potential tourist response remains rather limited (see Richardson and Loomis 2004; Scott et al. 2007a).

With its very visible sensitivity to variability in snowfall, winter sports tourism, and in particular the ski industry, has been repeatedly identified as highly vulnerable to changes in temperature and precipitation. Media prognostications in Europe, the United States, Canada, and Australia have declared climate changes could 'wipe out' large portions of the ski industry and discussed where it is safe to buy ski resort property, in order to avoid devastating future losses in real estate value. The CEO of Aspen Resorts has stated that "Climate change is the single biggest threat facing our business…" (Aspen Ski Company 2009). However, others have a very different perspective and remain largely unconcerned, at least publicly, about their capacity to cope with any future climatic conditions.

This chapter examines these differing perspectives on the climate vulnerability of the multi-billion dollar global ski tourism industry. Section 4.24.2 outlines the economic importance of ski tourism to mountain regions around the world and recent regional trends in visitation. Section 4.24.3 examines the evolution of the ski industry's climate sensitivity over the last three decades, and the adaptations that made this possible. The large literature on the climate vulnerability of the ski industry is then critically examined and the implications for future policy relevant research discussed in Section 4.24.4. In Section 4.24.4.1, a new sensitivity analysis framework is introduced to facilitate comparisons among future climate assessments in this sector. Recommendations for policy makers and ski industry stakeholders (see Section 4.24.5) conclude the chapter.

4.24.2 The Winter Sports Tourism Industry

While it is difficult to compare the economic size of the ski industry around the world because of the differences in the way ski industry is structured (single or multiple owners of ski lifts, on mountain restaurants and accommodations, ski schools, retail operations, etc.), and the quality of data, direct revenues by the global ski industry exceed US$9 billion each year. In the US, members of the National Ski Areas Association (NSAA) had direct revenues (not including real estate sales) of over US$3 billion in 2010–11 (IBIS World 2011). Ski areas in Canada reported revenues of approximately US$900 million in 2009 (Statistics Canada 2009), while a similar economic significance was reported for Australian alpine resorts in 2005 (Alpine Resorts Coordinating Council 2006). Decade old estimates by Lazard (2002) show the ski industry in Western Europe and Japan had annual revenues of over US$3 billion and US$1.4 billion, respectively.

The ski industry is considered a relatively mature tourism market, and while growth in the number of ski areas and skiers has continued in emerging markets (China, Southern America, Eastern Europe), in the major markets of North America, Europe, and Japan, the number of operating ski areas and ski participation has declined in the last decade. The United States has some of the best longitudinal data on the ski industry and this marketplace can be considered a reasonable proxy for the impact of economic and demographic trends on the ski industry in Canada, Western Europe, and Japan. In the United States, skier visits reached a new record in 2010–11 at 60.5 million, up from 57.4 in 2000–01 and 46.7 in 1990–91 (NSAA 2011). While positive, these figures do not reveal the demographic challenges the ski industry is facing. Ski participation surveys of the US population showed a different trend, with a decrease in the number of skiers–snowboarders from 12.9 million in 1990 to 11.6 million in 2006 (National Ski and Snowboard Retailers Association 2006). The average age of active skiers in the United States also continues to rise, from 33 in 1997–98 to 37 in 2006–07 (NSAA 2008). Similar trends have occurred in Austria, where skier surveys showed a decrease of young skiers (<30 years) from 29% in 1991 to 16% in 2007, and simultaneously an increase of skiers in the 50 years and older age group from 26 to 35% (Steiger 2012). These demographic trends and recent economic recessions and forecasts of limited economic growth over the next 10–15 years present important challenges to ski tourism demand in the US and other mature ski tourism markets.

How the impacts of salient long-term demographic and climatic drivers of the winter tourism sector will interact to influence ski tourism supply and demand remains an important uncertainty (Scott 2006).

4.24.3 Evolution of Ski Industry Climate Sensitivity

As the ski industry evolved throughout the twentieth century, the number of operating ski areas peaked in the 1970s and has gradually declined as many smaller ski areas closed, because of tremendous changes in the marketplace that required much greater capital investment in larger and faster ski lifts, rental equipment and terrain grooming vehicles, snowmaking, resort accommodations and other tourism services (spas, retail stores, restaurants, and entertainment facilities), and real estate development (condominiums, time-shares, and other properties). These and other technological and business strategies lessened the sensitivity of ski businesses to interannual variability of weather conditions by reducing the variability in the length of ski season, increasing the capacity of ski areas to accommodate greater numbers of skiers at a time (e.g., operational intensity), and diversifying income sources to increase non-weather dependent revenues (Scott and McBoyle 2007).

These advancements have reduced climate sensitivity. For example, average season length increased from the 1980s to the 2000s in all five ski regions of the United States (109–126 days in the Northeast, 90–103 days in the Southeast, 95–100 days in the Midwest, 127–138 days in the Rocky Mountains, and 118–136 days in the Pacific West; **Figure 1**), even though average winter temperatures were warmer in the 2000s in all of these ski regions. The variability in season length also declined in the 2000s. Other analyses in Eastern Canada (Scott 2006), Austria (Steiger 2011a), and Italy (Steiger 2011b) have similarly found that the sensitivity of ski operations to anomalously warm winter conditions has declined since the 1980s. This

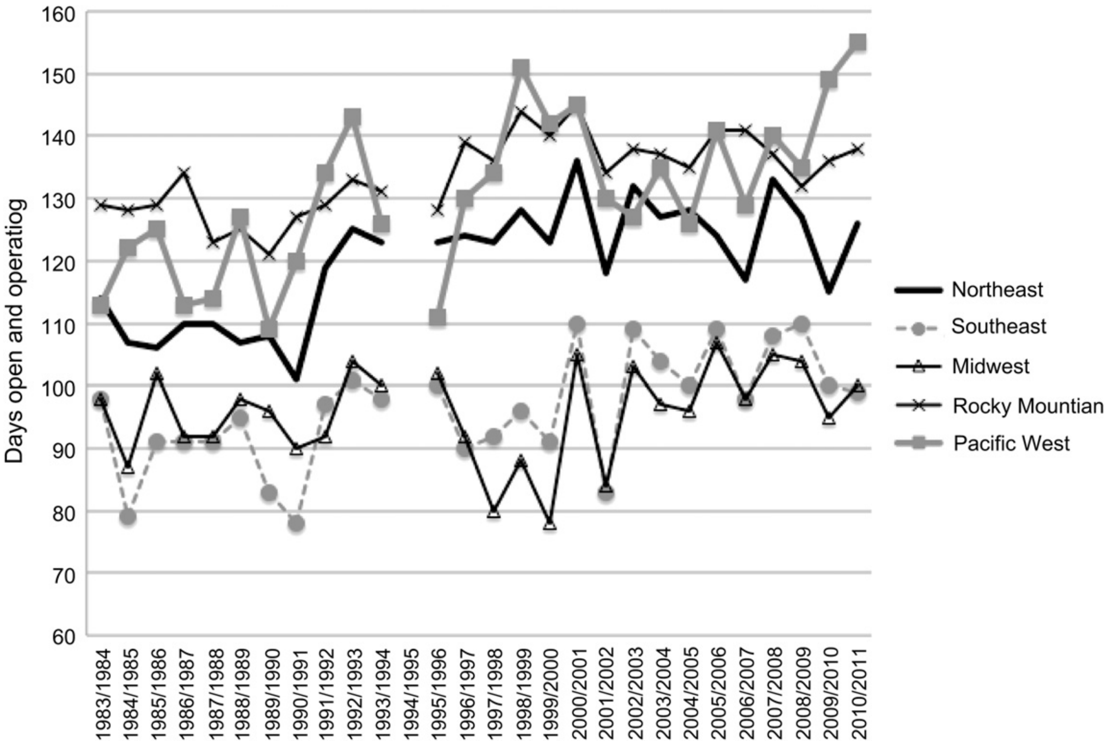

Figure 1 Ski season variability in US ski regions. Data source: National Ski Area Association – end of season survey reports 1983–2008

reduced climate sensitivity, including increased average season length and reliability of the ski season, particularly during winters characterized by high temperatures and low snowfalls, is directly attributable to the tremendous investments in snowmaking over the past two decades.

Snowmaking has become an integral climate adaptation in several major ski tourism regions. By the mid-1990s, more than 90% of ski areas in the lower elevation ski regions of the Northeast, Midwest, and Southeast had snowmaking capacity (Figure 2). Snowmaking is not as extensive in the higher elevation ski areas of the Rocky Mountains and Pacific Northwest regions, though it is used by the majority of ski areas in these regions at lower elevations. The proportion of skiable terrain covered by snowmaking in 2010–11 reveals the extent to which each of the ski regions rely on this technological adaptation: 74% in the Northeast, 98% in the Southeast, 82% in the Midwest, 13% in the Rocky Mountains, and 17% in the Pacific West. A similar east–west pattern exists in Canada (Scott 2006). In Australia, 100% snowmaking coverage is also common (Hennessy et al. 2008). In the European Alps, the proportion of skiable terrain with snowmaking is more similar to the higher elevation in the Western United States and Canada, but has expanded to over 70% in Italy, 65% in Austria, 36% in Switzerland, 21% in the French Alps, and 16% in Germany (CIPRA 2011).

It is important to note that while these adaptations to current climate provide the ski industry with some adaptive capacity in the decades ahead, the investments to reduce climate sensitivity over past three decades should not be construed as purposeful adaptations to some different future climate. Climate adaptations need to be capable of effectively dealing with all plausible future climate regimes and there is almost no evidence available that ski tourism operators have evaluated the design capabilities of their existing climate adaptations against the future range of climate possibilities. The following quote from a ski tourism operator in Tyrol, Austria, illustrates this difference very clearly (Trawöger 2011, p. 335):

> It would be presumptuous to say that the ski areas have taken precautions against climate change because we have not, we are not prepared. … Snow production may be a main strategy, but a strategy against a lack of snow, not against climate change. We have not taken any real precautionary measures against a marked warming trend yet.

4.24.4 Vulnerability to Climate

The climate vulnerability of the ski industry has been examined to some extent in 12 countries. These studies have consistently projected that the ski industry is at risk to decreased reliability of natural snow cover ('natural snow reliability'), shortened and more variable ski seasons, increased snowmaking requirements and decreasing snowmaking opportunities ('technical snow reliability'), and an overall contraction in the number of ski areas. The extent and timing of these impacts are highly uncertain, depending on the temperature and precipitation that actually occurs and whether the study accounted for snowmaking (see discussion below on the limitations of much of the extant literature).

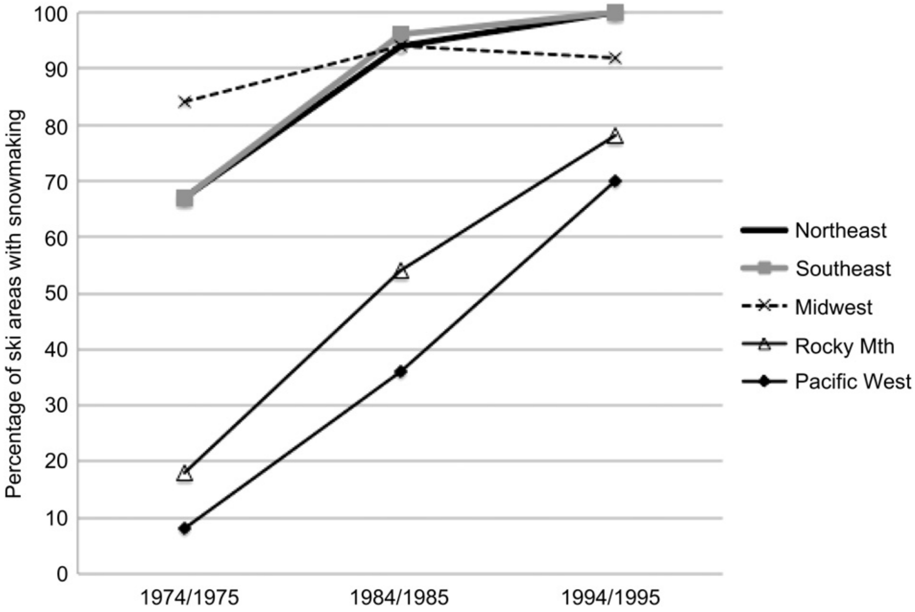

Figure 2 Diffusion of snowmaking capacity in the US ski industry. Data source: National Ski Area Association – end of season survey reports 1975–1995.

Climate assessments of the ski industry have utilized two main methodologies to estimate possible future changes in snow conditions and operational indicators (e.g., ski season length and snow reliable ski areas). Modeling-based analyses are the most common approach, and many of these studies suffer from two important limitations that reduce their validity and limit the relevance for decision makers. The use of inappropriate impact indicators is a first limitation. Some studies simply model natural snow conditions near ski areas without any specific indicators relevant to ski operations, such as the length of the ski season or opening – closing dates (e.g., Harrison et al. 1999; Uhlmann et al. 2009; Endler and Matzarakis 2011). Others utilize indicators that are not relevant to ski area operations, such as snow cover (which is a meteorological variable defined as 2.5 cm of snow, when ski operators require 30–100 cm of snow to open a ski run depending on terrain) (e.g., McBoyle et al. 1986; Lamothe and Periard 1988) or snow water equivalent on the first day of April (which is a widely used hydrological indicator for summer water supply in mountainous regions, but one that provides no insight into snow accumulation in the vital start of the ski season or the number of days with necessary operational snow depth) (e.g., Zimmerman et al. 2006). Yet others estimate ski season length solely on the basis of temperatures and rainfall, disregarding any measurement of snow depth and thus whether there is a snow product to ski on (e.g., Heo and Lee 2008). The second major limitation common too much of the literature, including the widely cited OECD analysis of the European Alps (Abegg et al. 2007) and all studies of the major ski regions in the western United States, has been the omission of snowmaking in regions where snowmaking is an integral adaptation to climate. Analyses that do not account for snowmaking, do not reflect the current operating realities of many ski operations, let alone their adaptive capacity 25 years from now, when studies have found most ski area managers plan to have enhanced snowmaking capabilities (Scott and Jones 2005; Wolfsegger et al. 2008; Hoffman et al. 2009), and consequently are of little use to the ski industry or policy makers.

State-of-the-art studies in Canada (Scott et al. 2003, 2007b), the United States (Scott et al. 2008), Australia (Hennessy et al. 2008), and Austria (Steiger 2010, Steiger and Abegg 2011) that have utilized physically based snow models to fully account for snowmaking as an adaptation have consistently found that the impact of warmer than current climate on ski areas was substantially lower than reported in studies that did not include snowmaking. However, in some regions, even with advanced snowmaking capacity, under the warmest mid-century scenarios, the ski tourism industry was found to be at risk of decreased reliability of natural snow cover ('natural snow reliability'), greatly increased snowmaking requirements and decreasing snowmaking opportunities ('technical snow reliability'), shortened and more variable ski seasons, and an eventual contraction in the number of ski areas. Lower elevation ski areas and the early portion of the ski season, including the economically important Christmas–New Year holiday period, were found to be at greater risk. Furthermore, the tremendous increase in snowmaking, particularly under warmer scenarios, necessitates greater examination of its sustainability in terms of costs and water and energy usage.

The second approach used to examine the impact of climate change on ski industry operations has been to examine the impact of anomalous climatic conditions, such as record warm winters or winters with limited or late snowfall, that could be analogs of possible future climate conditions. Analyses of recent record warm winters in North America (Scott 2006; Dawson et al. 2009) and the Tyrol region of Europe (Steiger 2011a,b) found ski seasons were shortened on average by only 4–10%, while snowmaking requirements increased. When examining the differential vulnerability of ski businesses, lower lying ski areas and smaller resorts consistently experienced the greatest loss in season length (Dawson et al. 2009; Steiger 2011a). Analog studies consistently found smaller losses in season length than modeling studies in the same regions. The differences can be explained by the inability of ski operations modeling to account for business decisions (e.g., opening under even very marginal conditions because of staffing inflexibility and to provide some level of skiing to guests staying in the resort), which can lead to the overestimation of season length losses. With improved cooperation of the ski industry, future analog studies could provide insight into the effectiveness of adaptive responses (from ski area operators, skier market segments, communities, and marketing organizations), identify key impact thresholds, and compare the relative vulnerability of different ski destinations.

The modeling and analog studies collectively reveal the differential vulnerability among ski areas and suggest that regional ski tourism markets have varied capacity to adapt to possible warmer conditions in the coming decades. However, the different snow modeling techniques, ski operations impact indicators, and climate scenarios used in the literature currently preclude accurate direct comparisons of the vulnerability of key ski tourism destinations or how regional ski markets are likely to evolve in response to future plausible climatic conditions. Such comparisons are necessary to assess the implications for tourism employment, real estate values, traffic congestion, development pressures (e.g., water requirements, access to higher terrain), and community and rural development planning.

4.24.4.1 Sensitivity Analysis

Here we introduce a new sensitivity analysis approach that utilizes industry relevant impact indicators (e.g., ski season length, snowmaking requirements) and the SkiSim2 ski operations model to facilitate inter-regional climate vulnerability comparisons across a wide range of potential climate futures. The diverse case studies of Vail (Colorado, USA) and Kitzbüehel (Austria) are used to illustrate the value of this comparative approach.

The SkiSim2 ski operations model uses a locally calibrated, physically determined snow model to simulate natural daily snow depth and snowmaking requirements for individual ski areas (across their full altitudinal range). See Steiger (2010) for more details on the development of SkiSim2 and the procedures to calibrate and validate the model for individual ski areas.

The model simulates the aim of ski area managers to maintain continuous operations between specified opening and closing dates (e.g., 1 Nov–31 March). Daily snowmaking occurs when the snow depth is insufficient for minimum specified operating conditions (e.g., 30 cm) and minimum temperatures required for efficient snowmaking are present (e.g., ≤ -5 °C). The maximum daily snowmaking output is also prescribed to represent that of advanced snowmaking systems (e.g., 10 cm day^{-1} over the skiable terrain covered by snowmaking). Snowmaking continues until a specified 'base layer' is established (e.g., typically 30–60 cm depending on terrain), which provides a dense snow base resistant to short mid-season melt periods and guarantees the planned season start. Further details on communications with the ski industry to establish key operational thresholds can be found in Scott et al. (2003) and Steiger (2010).

The climate stations used to represent the Vail and Kitzbüehel ski areas are presented in Table 1. The baseline winter climate at the two ski areas differs greatly. Although precipitation in the winter months is much higher at Kitzbüehel, snowfall and the number of snow days are much higher at Vail. This is attributed to the cold–dry continental climate of Vail versus the warm–humid climate of Kitzbüehel.

In Kitzbüehel, the ski season length modeled with the baseline climate (e.g., 0 °C and 0% precipitation change scenario) corresponds well with the average reported ski season, starting at the end of November and terminating in mid-April. In Vail, however, the reported average season length (mid-November to mid-April) is shorter than the modeled season length. Business decisions to close a ski area due to reduced skier demand and despite sufficient snow depth are common in late season (e.g., April–May). Skier demand is not incorporated in the SkiSim2 operations model and therefore explains the overestimation of season length in this case.

For this sensitivity analysis, a total of 49 climate scenarios were modeled using 2 °C temperature increments (ranging from -4 °C to $+8$ °C) and 10% precipitation increments (ranging from -30% to $+30\%$). For concise presentation, only

Table 1 Climate station and ski area statistics for Vail and Kitzbüehel

		Vail	*Kitzbüehel*
Climate station	Elevation (m)	2509	763
	Lat	39°38′N	47°27′N
	Long	106°22′W	12°24′E
	Mean temperature (°C) Nov–Apr, 1985–2001	−5.5	0.9
	Mean precipitation (mm), Nov–Apr, 1985–2001	264	470
	Mean annual snowfall (cm), 1985–2001	488	411
Ski area elevation (MASL)	Base	2470	778
	Top	3530	1995
	Mean	3000	1387
Average reported season length	From … to (days)	Mid-Nov to Mid-Apr (~152)	End-Nov to Mid-Apr (144 day average between 1982 and 2010)

the results for the mean altitude of each ski area are discussed (3000 MASL at Vail and 1387 MASL at Kitzbüehel. The climate scenarios were produced using the LARS-WG stochastic weather generator (Semenov et al. 1998).

The sensitivity analysis reveals that with the same advance snowmaking in place, Vail and Kitzbüehel differ greatly in their vulnerability to warmer climate scenarios (**Tables 2 and 3**). Applying the '100-days rule' – a coarse indicator of ski area profitability (Abegg et al. 2007) – Vail can be considered snow reliable in all of the climate scenarios (**Table 2**). Reductions in season length are minor in the +2 °C scenarios (up to 10 days), but in the +6 °C and +8 °C scenarios, the ski season could be shortened by up to 1 or 2 months, respectively. Current snowmaking technology is sufficient in Vail to maintain a 100-day season and to guarantee operations during the economically important Christmas–New Year period (Dec 22–Jan 4) up to a warming of +6 °C. Snowmaking requirements increase 59–94% in order to maintain ski season length and operations during this crucial holiday under a +6 °C scenario (**Table 4**). With no change projections for the State of Colorado exceeding +4 °C for the winter months by the 2050s, these results would indicate that the sustainability of skiing in the Vail area are more likely to be challenged by access to water for snowmaking or snowmaking costs than the physical ability to provide a reliable ski tourism product. These results also strongly contradict a highly publicized study by Zimmerman et al. (2006) that proclaimed the 'Ski Industry in Rockies May Be Shut Down by 2050,' even though it did not use any performance indicator relevant to the ski industry or account for snowmaking (**Table 5**).

The situation in Kitzbüehel is very different, as the sensitivity analysis reveals a high vulnerability to moderate temperature increases (**Table 3**). A 100-day season cannot be maintained with current snowmaking technology even under the +2 °C scenarios, though precipitation increases would help offset the negative impact of warming to some extent. In all

Table 2 Modeled ski season length including snowmaking in Vail (in days)

	−30% precipitation	*−20% precipitation*	*−10% precipitation*	*No change*	*+10% precipitation*	*+20% precipitation*	*+30% precipitation*
−4 °C	176	177	177	177	178	178	178
−2 °C	175	175	175	175	175	176	176
No change	168	169	170	170	171	171	171
+2 °C	161	162	163	163	164	164	165
+4 °C	149	149	146	148	151	152	154
+6 °C	134	136	136	137	137	138	138
+8 °C	111	111	112	113	114	115	116

Gray: shortening ski seasons.

Table 3 Modeled ski season length including snowmaking in Kitzbüehel (in days)

	−30% precipitation	*−20% precipitation*	*−10% precipitation*	*No change*	*+10% precipitation*	*+20% precipitation*	*+30% precipitation*
−4 °C	167	168	168	169	169	169	170
−2 °C	155	157	158	159	159	160	161
No change	135	138	140	141	142	143	144
+2 °C	75	79	84	88	91	94	97
+4 °C	0	1	3	5	6	8	10
+6 °C	0	0	0	0	0	0	0
+8 °C	0	0	0	0	0	0	0

Gray: shortening ski seasons. Black: ski season below 100 days.

Table 4 Modeled snow production requirements at Vail (in cm)

	−30% precipitation	*−20% precipitation*	*−10% precipitation*	*No change*	*+10% precipitation*	*+20% precipitation*	*+30% precipitation*
−4 °C	30	30	30	30	30	30	30
−2 °C	30	30	30	30	30	30	30
No change	31	31	31	30	30	30	30
+2 °C	32	32	32	32	32	32	32
+4 °C	48	37	34	34	34	33	33
+6 °C	94	91	82	80	70	68	59
+8 °C	111	108	105	102	100	97	94

Black: current snowmaking technology not sufficient to guarantee operation in the Christmas–New Year period (Dec 22–Jan 4). Gray: increases of snow production ≥50%.

Table 5 Modeled snow production requirements at Kitzbüehel (in cm)

	−30% precipitation	*−20% precipitation*	*−10% precipitation*	*No change*	*+10% precipitation*	*+20% precipitation*	*+30% precipitation*
−4 °C	30	30	30	30	30	30	30
−2 °C	31	31	31	31	31	31	31
No change	88	84	82	79	76	72	68
+2 °C	86	84	83	80	77	74	71
+4 °C	33	33	34	34	34	34	34
+6 °C	12	12	12	12	12	12	12
+8 °C	4	4	4	4	4	5	5

Black: current snowmaking technology not sufficient to guarantee operation in the Christmas–New Year period (Dec 22–Jan 4).

other temperature increase scenarios, current snowmaking technology is not sufficient and rapidly declines in volume because temperatures are too warm for efficient snowmaking (Table 5), and the ski season length is close to zero.

These results contrast a broad perception among Austrian ski area managers that snowmaking will provide sufficient adaptive capacity against any potential future climate warming. In a survey of Austrian ski area managers, Wolfsegger et al. (2008) found ski area managers were highly optimistic about their capacity to negate the impacts of a potentially warmer climate. With further adaptation, primarily snowmaking, but including other business and technical options, 68% believed that they could operate their businesses for another 30–45 years and 44% felt their businesses would be viable for at least another 75 years. Because Kitzbüehel is among the lowest major ski areas in Austria, it is more vulnerable than many others, but nonetheless, this analysis suggests ski area managers may be overestimating their adaptive capacity to climate.

The results of this sensitivity analysis for Vail and Kitzbüehel reveal the tremendously different potential for climate adaptation that exists within the ski industry. Kitzbüehel has considerably less potential to maintain ski operations under a warming climate than Vail, despite equal technical adaptive capacity prescribed in the model. Similar differences are also likely to exist between Kitzbüehel and the highest elevation ski areas in the European Alps, as well as between Vail and some lower ski areas coastal climate influence in the States of California and Washington. Further comparative analyses of other ski areas in each ski region, as well as the availability of resources (e.g., water for snowmaking), financial capacity (e.g., for snowmaking investments or infrastructure for non-snow-based tourism products), and social aspects (e.g., tourists response to ski area closures and more variable snow conditions), are needed to estimate the general adaptive capacity of the ski tourism industry in these regional ski markets.

4.24.5 Conclusions and Policy Implications

Based on the available literature on the climate vulnerability of the ski industry, with the possible exception of the Australian and Scottish ski industries, the entire ski tourism market is not at risk to plausible warming trends, but rather the risk is with individual ski operators and the communities that rely on ski tourism, in at risk areas. The probable consequence of warming would be a contraction in the number of ski operators in most regional markets. The impact is likely to be more pronounced at lower elevation ski areas and among smaller ski areas (Scott 2006; Dawson et al. 2009; Steiger 2011a), which have lesser adaptive capacity (see Scott and McBoyle 2007). This has potentially important implications for the development of future skiing demand, as lower elevations, particularly those closest to major urban markets, are often used for beginner ski runs. Whether fewer such ski areas would discourage beginner skiers or possibly diminish the industry's client base over time remains an important uncertainty. There are divergent views on the ski industry and government policies to manage this risk. Some regard a market-based contraction of the sector as healthy, while others contend that for regional economic development and the future of the ski industry, it will be essential to maintain these 'nursery ski areas' through subsidies (by government or the ski tourism industry) (Bürki et al. 2003; Scott et al. 2003, 2008). To some extent this has begun with local governments taking over the ownership of local ski areas and operating them on a non-profit basis like other recreational facilities (such as golf courses or parks) that are supported for the associated community health benefits. This is a policy discussion governments and the ski industry will need to engage in further, as there is tremendous pressure on aging recreation infrastructure in many developed countries and reduced budgets for recreation departments, which cannot prioritize facilities that cater to high cost forms of recreation.

Determining where the ski industry would most likely contract and where it could remain sustainable, if temperatures increase, is fundamental to decision-making and policy decision by the ski industry, investors, real estate developers, insurers, governments, and communities. Assessing the broader socio-economic implications of climate driven evolution of ski tourism markets at the community and regional level (e.g., employment, real estate prices, destination branding, development strategies, and visitation levels) should be a priority for these stakeholders. From a tourism planning perspective, communities that are at risk of losing ski resorts and those where ski resorts are likely to persist will need to adapt to any changes in climatic conditions, though for very different reasons. The former will need to adjust to reduced winter tourism spending, lost employment, and potentially declining real estate prices, and consider strategies for economic diversification and rebranding as a tourism destination (including new tourism product development). The latter will need to plan for increased tourism development pressures associated with the concentration of ski tourism in fewer areas, including water use for snowmaking, real estate development, slope expansion into higher terrain, traffic congestion, and tourist crowding. Adaptation policy will be required to guide the significant economic investment and environmental planning in these alpine communities.

It is essential to emphasis that although a large number of studies have examined the vulnerability of ski tourism to climate, many suffer from key limitations that reduce their validity and therefore limit the relevance for decision makers (e.g., the lack of relevant impact indicators and failure to account for snowmaking as an integral climate adaptation). Consequently, much of the media reporting on the climate impacts on the ski industry has been based on speculation and in some cases misinformation. There are real dangers to this type of misinformation. Flawed reports of impending doom for specific ski areas have been cited by articles in a travel magazine and international real estate investment web site that discussed 'where to buy ski properties to avoid global warming.' Readers are undoubtedly unaware that the statements of this report on some ski areas were scientifically baseless. Through our professional experience in Europe and North America, we have communicated with large investors that have become concerned by media stories on the risks of climate for ski areas. Some European banks imposed financing restrictions on low-lying ski areas based partially on the findings of early studies, which did not account for snowmaking. This misinformation has had a demonstrable impact on the ski industry.

The tourism industry is very image sensitive and is therefore very cautious about even acknowledging concerns about climate risks for fear of adversely affecting their reputation as a destination or as a sustainable business. Nonetheless, it is in the collective interest of ski industry associations, government tourism agencies, destination communities, and financial investors to support sound science on the vulnerability of ski tourism to climate, including the sustainability of key adaptation strategies. Surveys and interviews with tourism operators and industry associations indicate they believe that adaptation to future changes in climate is primarily the responsibility of governments (Scott et al. 2012). Therefore, government will need to provide leadership to facilitate the necessary collaboration among these diverse stakeholders, as well as the policy frameworks to foster sustainable adaptation strategies within the communities that are most vulnerable to large losses in winter tourism and those where ski tourism has the potential to persevere any plausible climatic condition in the coming decades.

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4.25 Mitigation and Adaptation Strategies to Reduce Climate Vulnerabilities and Maintain Ecosystem Services

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Glossary

Adaptation Adjustment in natural or human systems in response to actual or expected climatic stimuli or their effects, which moderates harm or exploits beneficial opportunities. Various types of adaptation can be distinguished, including anticipatory and reactive adaptation, private and public adaptation, and autonomous and planned adaptation (IPCC 2001).

Climate change A significant and lasting change in the statistical distribution of weather patterns over periods ranging from decades to millions of years. We focus largely on changes in temperature and precipitation, as they are changing in many regions and have direct impacts on ecosystems and human well-being.

Mitigation Actions that reduce the effects of humans on the climate.

Resilience Amount of change a system can undergo without changing state (IPCC 2001).

Sensitivity It is the degree to which a system is affected, either adversely or beneficially, by climate-related stimuli. The effect may be direct (e.g., a change in crop yield in response to a change in the mean, range, or variability of temperature) or indirect (e.g., damages caused by an increase in the frequency of coastal flooding due to sea-level rise) (IPCC 2001).

Vulnerability The degree to which a system is susceptible to, or unable to cope with, adverse effects of climate change, including climate variability and extremes. Vulnerability is a function of the character, magnitude, and rate of climate variation to which a system is exposed, its sensitivity, and its adaptive capacity (IPCC 2001).

4.25.1 Introduction

Virtually all regions of the earth are experiencing rapid changes in temperature, precipitation, and/or other aspects of climate. Human-caused changes in the earth's climate are greatly altering ecological systems, with consequences for human well-being. For example, recent studies have documented shifts in the distribution of plants and animals, advances in the timing of key ecological processes, and extinctions of wildlife populations and species that are likely linked to recent increases in temperature (Parmesan 2006). Such changes are creating regional combinations of environmental conditions that, within the next 50–100 years, may have no current-day analog. The resulting changes in ecosystem function will undoubtedly affect the provision of ecosystem services for human communities.

Maintaining or increasing ecosystem services into the future will require integrating adaptation strategies (actions that help human and natural systems accommodate changes) and mitigation strategies (actions that reduce anthropogenic influences on climate) (Figure 1). Mitigation strategies are those that reduce the magnitude of climate change that will occur. The vast majority of these strategies involve either reducing greenhouse gas (GHG) emissions or sequestering carbon, although they can address any human climate forcing. By contrast, adaptation can be defined as

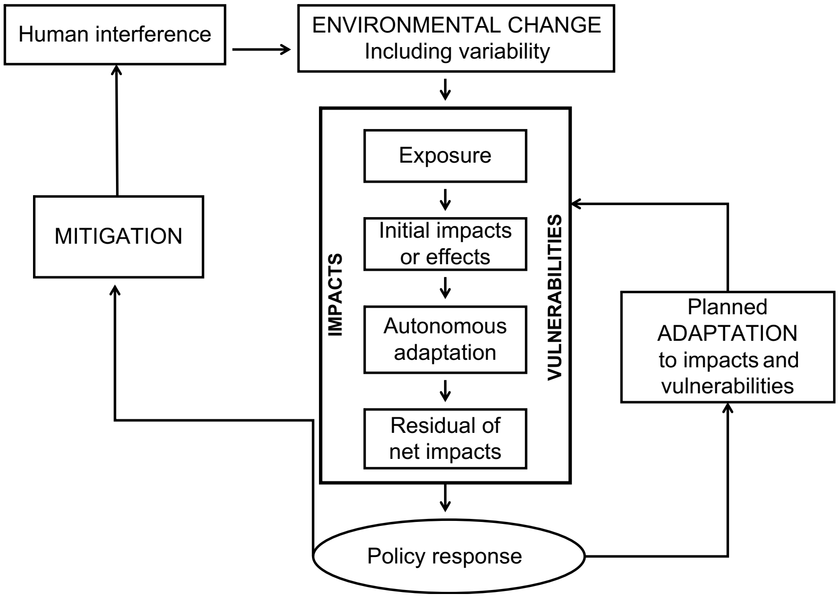

Figure 1 Conceptual diagram of vulnerability, mitigation, and adaptation options associated with climate change. Source: IPCC, 2001: *Climate Change 2001: Impacts, Adaptation, and Vulnerability.* Contribution of Working Group II to the Third Assessment Report of the Intergovernmental Panel on Climate Change. Cambridge University Press.

Table 1 Examples of mitigation strategies aimed at reducing GHG emissions or, in the case of the last category, sequestering carbon to reduce CO_2 concentrations in the atmosphere

Sector	*Mitigation strategies*	*Barriers to implementation*
Transportation	Walkable and bikable communities Increased vehicle efficiency	Lack of safe bike paths Political lobbying of car industry Lack of public transportation Poorly designed communities (sprawl) Cultural values
Shelter	Alternative building materials Passive solar heating Daylighting	Lack of incentives Restrictive building codes Cost of alternative materials
Food	Changes in diet Increased soil organic matter	Cultural values Mass media Demand for low-price food
Energy	Renewable sources Reduced consumption	Cost of new technologies Political lobbying of the energy industry
Carbon sequestration	Reforestation Reduced deforestation	Subsidized clear cutting

alterations to human or natural systems that are designed to reduce the negative impacts of – or exploit the opportunities created by – climate change (IPCC 2007a). Adaptation strategies are much more varied than mitigation strategies, as they are more often specific to particular systems or locations.

Mitigation and adaptation strategies designed to address changes in climate may have additional positive or negative effects on ecosystem functioning, ecosystem services, and human well-being. For example, replacing fossil fuels with renewable energy sources reduces GHG emissions while simultaneously reducing air pollution, acid rain, and smog, as well as asthma and respiratory ailments of humans. Conversely, coastal armoring, the building of seawalls, breakwaters, and jetties, may reduce damage to built structures from the combined effects of sea-level rise and storm surges but such actions can negatively affect coastal ecosystems.

In this chapter, we provide an overview of what will likely be some of the most effective and most important mitigation and adaptation strategies for addressing changes to the climate system stemming from increased GHG emissions. We attempt to cover the entire spectrum of life, from plants and animals to humans, as well as the geophysical properties of our planet that support these organisms. In relation to human populations, we focus primarily on human health as an index of well-being. We also introduce concepts of climate justice. Many of our examples are taken from the United States, although we also include other regions of the world in our analysis as appropriate. We discuss various ways in which mitigation and adaptation strategies can help reduce the magnitude and the impacts of the changes we are likely to experience, as well as improve human health and directly or indirectly affect ecosystem functions and services. Finally, although our analysis sets priorities and orders of importance for an ideal world unimpeded by political considerations, cultural differences, or economic limitations, we include a discussion of the social considerations that we believe must be incorporated into the development and application of mitigation or adaptation strategies.

4.25.2 Mitigation

In the following sections, we briefly discuss what will likely be some of the most effective mitigation strategies for addressing climate change, largely focusing on strategies to reduce CO_2 and other GHG emissions (Table 1). We have grouped these strategies into five categories: transportation, shelter, food, energy, and carbon storage and bioengineering. Although we focus on mitigation strategies that will reduce the magnitude of future climatic changes, we also discuss how these strategies can improve ecosystem functioning and, in some cases, human health.

4.25.2.1 Transportation

Transportation, the movement of people and goods, significantly impacts climate through the emission of GHGs. In 2004, transportation accounted for 23% of the world's energy-related GHG emissions and road transportation represented 74% of the total carbon dioxide (CO_2) emissions from transportation (IPCC 2007b). In addition to being a major source of emissions, transportation also significantly affects ecosystem functions and services. Pollution from vehicles affects ecosystem services such as clean air and water directly, and indirectly through impacts on the plants and animals that regulate ecosystem function. As species are lost from or move into ecosystems the functioning of those systems can change, resulting in altered ecosystem services. Human health is likewise affected by pollution from vehicles (e.g., through chronic lung disease). Transportation networks and moving vehicles also fragment landscapes, reducing the flows of energy and biota resulting in isolated populations and potentially making these populations vulnerable to extirpation and impairing ecosystem functions.

Mitigation strategies that address transportation can be placed into three basic categories: those that increase the efficiency of particular transportation approaches, those that result in a shift in the mode of transportation, and those that reduce the amount of transportation that is needed. Here, we briefly summarize some of the most important mitigation strategies for each category.

4.25.2.1.1 Vehicle Efficiency

A large reduction in GHG emissions can be accomplished by increasing the fuel efficiency of vehicles. For example, increasing the efficiency of light-duty vehicles (cars and small trucks) has the potential to reduce their carbon emissions by up to 50% by 2030 (IPCC 2007b). Such efficiencies can be attained by a combination of reducing vehicle weights, increasing aerodynamics, increasing engine efficiency (particularly diesel engine efficiency), and increasing the use of biofuels and electric and hybrid vehicles. In 2006, the International Energy Association projected that the proportion of transportation energy supplied by biofuels could be increased to 10% (IEA 2006a). Although there is good evidence of successful biofuel markets and programs (e.g., ethanol from sugarcane in Brazil, Goldemberg 2007), there are also negative consequences of increased biofuel production for biodiversity and carbon storage (Fargione et al. 2008; Fletcher et al. 2010). One opportunity for transportation mitigation strategy is the promotion of behavioral changes of drivers. Efficiency of road vehicles could be improved by 5–20% by changes in driving styles, improved maintenance, more efficient tires, reduced idling, and traffic design and maintenance (IPCC 2007b).

4.25.2.1.2 Modes of Transport

A second approach to reducing emissions and many of the other effects of transportation involves changing the ways in which people and goods are moved. One such approach is to increase the use of public and human-powered transportation. Increasing the amount of walking, biking, and use of public transit will depend largely on the available infrastructure and the capacity to provide it. Supporting the development of 'walkable' cities and neighborhoods, bike-friendly roadways and bike paths, carpooling and car-sharing programs, and efficient and safe mass transit are all approaches for shifting the mode of urban transport.

Present transportation alternatives vary by country, with Europe, Japan, and many developing countries having the highest levels of public transportation use, and the United States having the greatest use of personal automobiles. In some developing countries, such as Vietnam or China, personal automobile use is a recent phenomenon, and personal motorized transport is a high aspiration because it conveys increased social status. This disparity in the historical development of the transportation sector will mean that mitigation strategies, barriers, and solutions will have to be location specific and may be dynamic over time.

In addition to the reduction in emissions and the other environmental benefits of shifts to more human-powered transportation, such changes also have clear human health benefits resulting from increased exercise, weight management, and decreases in air pollution (Nemet et al. 2010). Simultaneously improving the quality of public transport and leapfrogging transport-intensive stages of economic growth is needed in many countries to increase higher levels of mass transit use and human-powered transportation (Wright and Fulton 2005). Further reductions in emissions can be made by changing modes of transport for other transportation such as moving more freight by train and ship and less by truck.

4.25.2.1.3 Transportation Demand

The third way to reduce transportation-related GHG emissions is to reduce the amount of transportation that is needed. Decreasing the demand for transportation largely involves changes in human behavior, urban and landscape planning, and changes in technology. Sprawling, low-density urban neighborhoods, such as those found in the United States, perpetuate automobile dependency and transform ecologically functional landscapes into subdivisions. Compact, high-density communities with local urban centers allow residents to work and live in close proximity, and help build social capital among residents and protect natural areas. In conjunction with human-centered transportation infrastructure such as sidewalks, bike lanes, and public transportation, compact neighborhoods reduce car dependency while simultaneously improving the physical fitness of residents. Public green space and urban forests sequester carbon while improving air quality and mental well-being. Increased vegetation, shade trees, and less asphalt combat urban heat-island effects and reduce energy demand for cooling buildings.

Advances in communication technologies also have the potential to reduce the need for transportation. The Internet, online meeting, document sharing, and conference tools have led to an increase in telecommuting and web-based meetings. Similarly, online meetings have begun to replace some in-person meetings and have the potential to dramatically reduce air travel, which can account for a significant portion of an individual's carbon footprint (Fox et al. 2009).

4.25.2.1.4 Barriers and Opportunities

The most significant barriers to implementing mitigation strategies in the transportation sector are long-established personal transportation behaviors and the lack of government interest or capacity to invest in new technologies. Changing the way and the amount that people move around will be very difficult. In the United States and elsewhere, people's relationships with the automobile involve issues of convenience, independence, safety, and social status. Changing these relationships will involve making forms of public transportation more convenient, more effective, and more appealing. Rising fuel costs and commute times may provide some opportunity for implementing transportation-based mitigation strategies. Failing automobile industries and economic crises may provide another. Similar to the projects undertaken by the Civilian Conservation Corps in the United States in the depression of the 1930s, modern-day work relief programs could be used to transform transportation systems. Short of such crises, major changes in transportation will take a combination of regulatory action, education, and incentive programs.

4.25.2.2 Shelter

Housing is one of the most idiosyncratic and regionally variable aspects of human culture. The design of structures is dependent on local climate, land access, available materials, and regional architectural histories. Much of the recent human-caused change in climate stems, in large part, from the way we design, construct, and inhabit the built environment. The following section focuses on a representative selection of design strategies that mitigate the built environment's contribution to carbon emissions and, in many cases, provide cobenefits to human health and local/regional ecological resilience.

4.25.2.2.1 Carbon-Conscious Materials

Building material extraction can have profound impacts on ecosystems and ecosystem services. Mining degrades natural landscapes, destroys habitat, pollutes freshwater environments, and can expose human populations to toxins. Poorly managed lumber extraction leads to deforestation, eliminates suitable habitats, erodes soils, and diminishes the earth's carbon sequestration capacity. Mines that observe best management practices such as land reclamation have fewer negative impacts on climate, local ecosystems, and human health. Sustainably harvested lumber can act as a long-term carbon sink and contribute to the productive and ecological resilience of forests. Rapidly renewable lumber alternatives such as bamboo can offset the demand for slow-growing trees species, rebuild soils, and set the stage for reforestation. However, as with any renewable resource, expanding the production of bamboo in monocultures has the potential to eliminate and/or degrade existing ecosystems.

Eight percent of annual carbon emissions worldwide can be attributed to building material extraction, production, transportation, and installation (Mazria and Kerschner 2008). Choosing building materials with low embodied energy (the cumulative energy of extraction, production, transport, installation, and disposal) and/or that use alternative energy sources reduces the building sector's carbon footprint. Locally sourced materials produce fewer carbon emissions than those transported long distances and both durable materials and those with recycled content help reduce demand for virgin materials. Fully recyclable materials can be reprocessed and repurposed with low energy inputs indefinitely. Removing toxic compounds from material production processes and building products facilitates the recycling or biodegradation of building components. It also helps prevent air and waterborne industrial pollution and associated human illness.

In some cases, it may be possible to choose building materials that actually sequester more carbon than is emitted in their production. The production of Portland cement, the most commonly used cement in construction, is a relatively large source of CO_2 emissions. Magnesium oxide-based cement is as strong as normal Portland cement, but can be manufactured at low temperatures using renewable energy sources. Magnesium oxide is an abundant mineral and is easily recyclable (Smith 2005). As it cures, it absorbs more CO_2 than is released during its production, resulting in a net negative carbon budget.

4.25.2.2.2 Regenerative Buildings

The average lifespan of buildings in the United States is less than 50 years (O'Connor 2004). Design for adaptation – design that easily accommodates changes in configuration and use – extends the life of buildings and stems demand for new construction and virgin materials. When buildings are ultimately decommissioned, design for disassembly facilitates the breakdown and reuse of their constituent components. Both design for adaptation and design for disassembly act upstream from recycling as part of a multicyclic system that repositions well-weathered buildings and building materials as resources rather than wastes, reducing carbon emissions in the process.

Building operations such as heating, cooling, and lighting account for 42% of electricity consumption in the United States (Mazria and Kerschner 2008). Passive design strategies can drastically reduce a building's dependence on carbon-intensive energy production. In cold climates, airtight, well-insulated building envelopes can work in tandem with building orientation, thermal mass, and passive solar radiation to provide thermal comfort and reduce heating bills. In hot climates, external shading, light colored/reflective roofs and walls, and passive ventilation strategies can reduce cooling loads. Daylighting strategies such as light shelves and shallow floor plans bring natural light into interior spaces, reducing the demand for electrical lighting while, at the same time, contributing to the well-being and productivity of building occupants.

Similar to the use of building materials to sequester more carbon than they produce, buildings can generate more energy than they consume. Buildings equipped with photovoltaics, wind turbines, and fuel cells are some of the energy producing technologies that make this possible. Recent advances in computer-aided design software help designers address building performance issues early in the design process and optimize building design for energy use and production. Improvements in digital monitoring and analysis allow occupants to scrutinize building performance and optimize energy use once buildings are operational. In the future, smart buildings and systems will likely respond dynamically to human occupation, weather, daily cycles, and seasonal change, further reducing their energy footprint.

4.25.2.2.3 Compact Communities/Integrated Landscapes

Compact communities (discussed in the transportation section, above), land-use planning, and high-density zoning have the potential to reduce CO_2 emissions, reduce sensible and latent heat fluxes, and improve human health and ecosystem function. Centralized infrastructure and zoning laws that segregate industrial, commercial, agricultural, and residential land use can be beneficial to public health within localities. However, these practices also create a cognitive disconnect between human action and its environmental consequences. They facilitate the transfer of local environmental burdens to regional and global scales, contribute to climate change, and undermine the health of vulnerable populations. Integrated land use and responsibly managed distributed ecological infrastructure have the potential to safeguard public health without the transference of environmental burdens. Synthesizing commercial, industrial, agricultural, and residential precincts, reimagining landscape as infrastructure, and bringing utilities into the public realm raises awareness about the causal relationships that link human activities, environmental degradation, and human health. Urban agriculture, for example, reduces dependence on carbon-intensive industrial food production, minimizes the carbon footprint of food transport, teaches urbanites how to grow their own food, and provides nutrition to communities.

Carbon-conscious materials, regenerative buildings, compact communities, and integrated landscapes have the potential to mitigate the worst effects of climate change. Their success will depend on the ability to implement them not only in developed countries but also in the burgeoning cites of the Global South. We must adapt these strategies to diverse climates, contexts, and cultures and pursue them in tandem with issues of economic development and social equity.

4.25.2.2.4 Barriers and Opportunities for Housing Mitigation Strategies

In modern history, land distribution and regulation have always been the prerogative of governments. For this reason, national, regional, and local governments have a large role to play in housing mitigation strategies. Governments control land-use planning, zoning, and building-code regulations. The ability to act on the mitigation strategies identified above, therefore, is largely dependent upon the regulatory and enforcement environment in a region. In a democratic society, these will in turn be dependent upon the inclination and ability of the state to assume progressive and proactive attitudes toward mitigation.

4.25.2.3 Food

Agriculture releases considerable amounts of GHGs into the atmosphere. In 2005, it accounted for 10–12% of the total global anthropogenic GHGs including approximately 60% of nitrous oxide (N_2O) and 50% of methane (CH_4) of the anthropogenic totals (Rosenzweig and Tubiello 2007; Smith et al. 2008; Burney et al. 2010). Land-use change, nitrogenous fertilizer applications, livestock production, rice farming, and biomass burning are among the major direct sources of GHG emissions. Indirect sources of GHGs from agriculture include the production and/or applications of fertilizers and pesticides, the operation of farm machinery, and the transportation of agricultural products (Burney et al. 2010).

There are multiple opportunities for mitigating climate change impacts through modifications in agricultural practices and food consumption. With respect to agricultural production, mitigation strategies include soil carbon sequestration and the reduction of GHG emissions through altered production methods. With respect to food consumption, society can mitigate the impacts of climate change through changes in diet and by reducing the amount of transportation needed to deliver food (e.g., increasing local food production). Below, we discuss several of these mitigation strategies. The topic of increasing local food production is covered in previous sections on transportation and shelter.

Unlike housing, food is a sector that is potentially much more amenable to individual decision-making and personal choice. This will depend on the relative proportion of food in a household budget. While Americans spend only 5% of their incomes on average on food, the figure for Indonesia is 30%. This indicates that people from wealthy countries would have greater flexibility to support alternative and nonindustrial agriculture through consumer preferences than those from countries where food is a larger part of household budgets.

4.25.2.3.1 Soil Carbon Sequestration by Soil Organic Carbon Management

Agricultural and degraded soils can act as large carbon sinks with the potential to sequester 55–78 Gt of carbon globally (Lal 2004). Soil organic carbon (SOC) is the major component (62%) of this large soil carbon pool (Lal 2004). SOC accumulation is facilitated by adding biomass to the soil and minimizing soil disturbances. The increased SOC improves the physical, chemical, and biological properties of the soil and in turn enhances crop productivity, water holding capacity, and land sustainability under a low-input cropping system. Several agricultural practices facilitate accumulation and retention of SOC in cropland soils, e.g., conservation tillage, mulches, cover crops, manuring, crop rotations, and agroforestry (Lal 2004).

The benefits of these agricultural practices go beyond carbon sequestration. They have the potential to reduce erosion, limit positive feedbacks in drought cycles, and benefit human health. Over the past 40 years, 30% of the world arable land has been taken out of production as a result of erosion (Pimentel 2006). Conventional agricultural practices involving frequent tillage result in soil erosion, which in turn increases concentrations of airborne particulates. These particles can carry pathogens causing infectious diseases and can provide positive feedbacks to drought conditions. Recent climate modeling has demonstrated a positive feedback in the 'dust bowl' drought of the 1930s in the United States (Schubert et al. 2004; Cook et al. 2009). Cook et al. (2009) discovered that a reduction in vegetation cover and the addition of eroded soil dusts to the air resulted in a high temperature anomaly over the northern United States and intensified the drought. As a result of the dust bowl, more than 50% of the surveyed farms comprising 8.7 million acres were seriously eroded, and the economic loss was valued close to US$200 million (AAAS 1936). A combination of warming, drought, and conventional agricultural practices together have the potential to re-create the dust bowl of the 1930s in the Great Plains of the United States (Rosenzweig and Hillel 1993).

4.25.2.3.2 Reduction of GHG Emissions Associated with Livestock Production Systems

The livestock industry is a main contributor to three major climate-related problems associated with global food systems: GHG emissions, reactive nitrogen mobilization, and plant biomass appropriation (Pelletier and Tyedmers 2010). Increases in livestock production and meat consumption are also blamed for the evolution of new and virulent emergent diseases. Any improvement in the environmental sustainability of livestock production will concurrently have a benefit for human health.

Pelletier and Tyedmers (2010) estimated that globally the livestock sector contributed 14% of anthropogenic GHG emissions, 63% of reactive nitrogen mobilization, and consumed 58% of human-appropriated biomass as of 2000. Reduction in GHG emissions in agriculture can be achieved by developing strategies involving improved production efficiency, land-use changes, cropland and rangeland management, and livestock and manure management (Rosenzweig and Tubiello 2007; Smith et al. 2008; Burney et al. 2010; Pelletier and Tyedmers 2010). For example, enhancing production efficiency through agricultural intensification has been credited with the avoidance of 161 Gt of carbon emission globally since 1961 (Burney et al. 2010). This figure highlights that the investment in agricultural research to improve the environmental sustainability of global food production systems (i.e., livestock, crop, and aquatic systems) should be a prioritized mitigation strategy (Lobell et al. 2008; Burney et al. 2010;

Steinfeld and Gerber 2010). Another mitigation strategy to reduce emissions involves shifting livestock production regimes from ruminants to more efficient and lower impact monogastric species (e.g., poultry), well-managed fisheries and aquaculture, and promoting plant-based protein sources (Pelletier and Tyedmers 2010; Steinfeld and Gerber 2010).

4.25.2.3.3 Diet

Changing livestock production from ruminants to monogastric animals and reducing livestock production overall both require significant changes in diet in many parts of the world. This is, of course, where tradition and culture play an important role, yet it is not impossible to induce dietary changes.

Initiatives that reduce the consumption of meat could have dramatic effects on GHG emissions particularly in developed countries (McMichael et al. 2007). Such policies would also reduce impacts on ecosystems and promote other ecosystem services such as a reduction in the clearing of Amazonian rain forests, reduced nitrogen deposition, and a reduction in the application of high-phosphate fertilizers used to grow feed. Reduced meat consumption could also improve human health in developed countries particularly when coupled with incentive structures and educational measures to replace high-fat, sugar-rich foods with more complex diets based on plant proteins. Reduced red meat consumption will likely lower the risk of obesity, diabetes, and several types of cancer (and specifically colorectal cancer), and may reduce the risk of ischemic heart disease (McMichael et al. 2007).

A shift from meat-based proteins to plant-based proteins has the potential to substantially increase the total food calories available for consumption worldwide. Worldwide educational efforts, altered trade policies, shifts in farm subsidies, public health campaigns and new environmental stewardship programs will be needed to achieve a fundamental change in the consumption of meat to achieve large-scale cobenefits for the environment and human health.

4.25.2.4 Energy

Energy consumption and production affect carbon emissions, which in turn affect human health and ecosystem functioning and services. These effects can be divided into the influence of energy consumption and production. While human well-being is in many ways positively affected by the increased availability of energy, there are also negative health effects resulting from the energy consumption and production. Below, we describe potential mitigation strategies for the energy sector.

4.25.2.4.1 Energy Consumption

The US Energy Information Administration reports on energy consumption in the United States in four sectors: residential, commercial, transportation, and industrial. In 2009, consumption across the four sectors accounted for 22, 19, 29, and 30% of overall energy consumption, respectively (US Energy Information Administration 2010). Overall energy consumption, as well as CO_2 emissions from energy consumption, continues to rise. Total US CO_2 emissions from energy consumption were 1390 million metric tons of carbon in 1990 and 1586 million metric tons in 2008 (Research and Innovation Technology Administration 2011).

Reducing GHG emissions through declining energy consumption can be accomplished through a combination of technological advances and changes in human behavior (including the adoption of new or alternative technologies). Several mitigation strategies for addressing energy consumption have been provided in the previous sections on transportation and shelter. In addition to those strategies, increasing the efficiency of appliances and lighting is likely to provide significant reductions in GHG emissions. The most efficient appliances in use today use half to one-fifth of their most inefficient counterparts currently in use (IPCC 2007b). In developed countries, substituting smaller and more efficient refrigerators, washing machines, and other appliances for less efficient ones can substantially reduce energy use. In addition, in developed countries, improvements in the efficiency of electronic devices with inefficient standby modes and power supplies (or more simply unplugging these devices when not in use) can significantly reduce energy consumption. In developing countries where biomass (e.g., wood, dung, and charcoal) is used for cooking fuel, substantial reductions in GHG emissions and improvements in human health may be attained by increasing the efficiency of biomass stoves, fostering a shift to cleaner burning liquid and gaseous fuels, and improving access to electricity (IPCC 2007b).

Significant reductions in emissions can also be made through the use of more efficient lighting. The emissions from electric lighting worldwide are equivalent to roughly 70% of those generated by light passenger vehicles (IEA 2006b). Substituting more efficient lighting technology (e.g., compact fluorescent bulbs and occupancy detectors) can reduce residential energy use by a factor of four or five (IPCC 2007b). Programs designed to increase the energy efficiency of appliances, vehicles, and lighting (e.g., the Energy Star and vehicle fuel economy (CAFÉ)) also have the potential to reduce GHG emissions. Although such programs have not decreased energy use in the United States, they may be partially responsible for halting the growth of per capita energy consumption (US Energy Information Administration 2009).

4.25.2.4.2 Energy Production

Methods for reducing the impacts of energy production on atmospheric CO_2 concentrations, human health, and the environment focus primarily on improvements in an increased generation of renewable energy. Renewable energy sources include those based on waves and tides, biofuels, solar, wind, and hydropower. A shift to renewable energy sources has great potential to reduce GHG emissions, reduce impacts on ecosystems and ecosystem services, and improve human health. Nonetheless, the production of renewable energy will have adverse effects on some ecosystems. Below, we discuss some of the benefits and potential side effects of some sources of renewable energy.

In regions of large tides and tidal currents, such as the United Kingdom, tidal energy could supply as much as 10% of the country's energy supply (Blunden and Bahaj 2007). Two types of systems are in use or are proposed, the tidal barrage and tidal turbines. Tidal barrages allow water to flow into a bay or estuary during flood tide, then they release the water back during ebb tide. As water is released it flows through turbines generating energy. The impact of barrages on fish may be substantial (Aprahamian et al. 2010). Power can also be extracted in the marine environment by turbines in regions of high wave and current energy. However, the ecological impact of the extraction of energy in highly energetic environments is not clear (Shields et al. 2011). The effects of such installations include alteration of benthic (ocean bottom) environments through changes in sediment transport and detrimental impacts on intertidal species through altered currents and nutrient flows.

Biofuels (discussed briefly in Section 4.25.2.1 Transportation) include corn- and sugarcane-based ethanol, wood-based methanol, biodiesel from soy, rapeseed oil, and switchgrass. Biomass is also used in cofiring (combining with coal or other fossil fuels in the burning process) or burned alone as a fuel. Crops can be grown explicitly for biofuels, or residues from farming or forestry can be used as biofuels. Biofuels can also be converted into gasses and then used to fuel gas engines. Nonetheless, many biofuels require significant amounts of land and water to grow them, which brings fuel production into conflict with food production as well as potentially result in a climate effect from the alteration in the surface fluxes of heat and moisture into the atmosphere. In addition, fuel plants may not be as effective as others at absorbing GHGs, and more natural lands converted to agriculture for biofuels will result in increased erosion, decreased water quality, and a loss of wildlife habitat and biodiversity.

Solar energy can be used to generate electricity, heat water, and heat buildings and can be a highly effective form of renewable energy in some regions. Although photovoltaic power generation only accounted for 0.004% of world power production as of 2007, expansion is occurring at roughly 30% per year, largely in developing countries (IPCC 2007b). Hot water production is the second single largest use of energy in residences in both the United States and China. Solar water heating is a cost-effective alternative to other fuel sources in many locations. Similarly, passive solar heating of buildings (mentioned in the Section 4.25.2.2 Shelter) is an effective heating measure in many regions. Finally, solar energy can be used to generate power with solar thermal electric plants that focus solar rays to heat a liquid, which is then used to generate electricity. Passive solar space heating and hot water production likely have the lowest environmental costs. Decentralized photovoltaic use on residences and buildings incurs environmental costs in terms of the production process, but likely have few other negative effects. Conversely, photovoltaic fields and solar thermal electric plants can have large footprints, adversely affecting plant and animal habitat.

Like solar power, wind-generated power is more effective in some areas than others. Wind produced 0.5% of global electricity in 2004 but has been growing at a rate of approximately 28% per year since 2000 (IPCC 2007b). There are potential adverse effects on birds, through collision, displacement due to disturbance, barrier effects, and habitat loss, with more research needed in all areas (Drewitt and Langston 2006; Fox et al. 2006). In addition, the impact of wind turbines on views is perceived to be a substantial barrier to implementation in some communities (Wolsink 2007).

As of 2004, hydropower accounted for 16% of global electricity (IPCC 2007b). Together, large hydropower plants and small and micro hydropower systems can supply power to large municipalities and isolated rural communities with relatively few emissions. Hydropower is not carbon neutral, however, and some studies have estimated significant emissions from hydropower reservoirs (IPCC 2007b). In addition, dams and reservoirs fragment river networks, alter natural flows of water and sediments, and change stream temperatures. These effects are discussed in Section 4.25.3.5 Human-Dominated Systems.

There are several other major renewable energy sources including nuclear, hydrogen, and geothermal. As with the renewable sources described above, there are both benefits and costs to using these other renewable energies.

4.25.2.5 Carbon Sequestration and Geoengineering

Most of the mitigation strategies discussed above are focused on reducing GHG emissions. Additional strategies can be used to increase carbon sequestration, removing CO_2 from the atmosphere. Below, we discuss a few strategies that have been proposed for increasing carbon sequestration and storage as well as much riskier geoengineering proposals.

4.25.2.5.1 Forest Protection Reforestation

Deforestation is one of the largest sources of emission accounting for over 8 Gt CO_2 per year in 2000 (Stern 2006). Although there are many other uses of natural resources that result in carbon emissions, here we focus on mitigation strategies that focus on deforestation. Given the slow rate at which trees absorb carbon dioxide, simply planting new trees in place of those removed does not immediately offset the removal of a tree. A more rapid approach to mitigation is to reduce deforestation. Unlike the majority of emissions that emanate from industrialized countries, most emissions from deforestation are generated by developing countries. Deforestation also itself alters the climate system (Pielke et al. 2007).

Reduced Emissions from Deforestation and forest Degradation (REDD+) is a program of the United Nations that seeks to mitigate climate change by providing incentives to conserve forest cover. Given recognized challenges in REDD (Dickson et al. 2009) – including country by country differences in who owns the forest, who should receive the monetary benefits of preserving the forest, and the reliance of various indigenous groups on forests for livelihood and cultural identity – the program was modified to REDD+ in 2010 to minimize negative consequences and respect the rights of indigenous peoples and members of local communities (Kanninen et al. 2010). Assumed cobenefits include the suite of ecosystem services such as watershed protection; reduction of soil erosion; flood control; provision of fuel, timber, and foods; and cultural and spiritual amenities for local communities. Biodiversity is presumably also enhanced by protecting natural systems. It is possible that forest-dependent communities will be able to maintain access to forests through this initiative. Potential co-harms are increased demand for conversion of other ecosystems if forests are protected, replacement of mixed stands with plantations, and benefits accruing to those not responsible for care and maintenance of the forests.

Prevention of deforestation mitigates atmospheric CO_2 concentrations by preventing the release of stored carbon that occurs when forests are harvested and protecting forest stands that absorb carbon, as well as limits changes in surface energy

Table 2 Examples of adaptation strategies that allow ecosystems and human communities to adapt to uncertain future environments

System	*Adaptation strategies*	*Barriers and challenges*
Freshwater	Increasing connectivity Riparian restoration	Slow uptake of private–public partnerships for restoration
Terrestrial	Protected areas Connectivity	Land costs Extent of land development Property rights arguments
Coastal	Coastal restoration and protection Translocation of people and ecosystems	Few demonstration projects Demand for coastal development
Human dominated	New dams Shifts in the distribution of agriculture	Growing demand for food Growing demand for water

and water fluxes. As of 2011, South America and Africa continue to have the largest net loss of forests and large decreases in carbon storage (FAO 2011). Although tropical forests have been the focus of early REDD efforts, recent evidence indicates that a large amount of carbon can be stored in mangrove forests (Donato et al. 2011), peatlands (Dise 2009), and boreal forests (Carlson et al. 2010), making these potential targets for conservation efforts. Urban forests have also been largely neglected as a potential carbon sink. Escobedo et al. (2011) review the services and disservices of urban forests combined with human health and pollution mitigation as well as carbon sequestration. In some locations, urban forests are on par with other techniques for carbon sequestration and reduction.

4.25.2.5.2 Other Forms of Carbon Capture

In addition to capturing carbon in plants, it may be possible to increase carbon storage in the water and in the earth's crust with various methods. These proposed approaches are still on the scientific fringe and considered to be highly unproven and/or potentially quite risky. One such approach is to capture carbon in the oceans through iron fertilization. In regions of the ocean where there are ample nutrients to drive primary production (photosynthesis) but observations show that chlorophyll is relatively low, the lack of iron is thought to limit the productivity. Over the last two decades, several experiments have attempted to determine whether the addition of elemental iron into the water could cause an increase in algal production and ultimately, as photosynthesis fixes carbon into organic molecules that then sink, the sequestration of carbon in deep ocean sediments. However, the results of these experiments are mixed (de Baar et al. 2005), with the export of carbon being difficult to assess and likely quite modest. At the same time, the impacts on local ecosystems and thus ultimately fisheries in potentially highly productive regions of the subpolar oceans are not yet known. Other carbon sequestration approaches have also been proposed including pumping air down into the oceans, injecting carbon into the ground, and incorporating biochar into soils.

4.25.2.5.3 Geoengineering

Given the magnitude of projected changes in climate and the difficulty in implementing meaningful mitigation measures, some scientists have argued for large-scale efforts to reduce the amount of incoming solar radiation. These approaches are collectively referred to as geoengineering. At present, these approaches are unproven, risky, and, at best, will only address some of the impacts of the human influence on climate. One such geoengineering approach would inject sulfate aerosols into the stratosphere. These aerosols would reflect incoming solar rays and reduce warming. Although such an approach might reduce average global temperatures, it would also likely decrease average global precipitation (Bala et al. 2008) as well as alter atmospheric and ocean circulation patterns. For a given change in radiative forcing, solar forcing is more effective at changing the hydrological cycle than forcing from carbon dioxide owing to differences in the surface latent heat (and thus evaporation) response. While the impact of carbon dioxide fertilization could increase net primary production in terrestrial ecosystems (Govindasamy et al. 2002), ecosystems could continue to be vulnerable due to changes in water resources. In addition, solar radiation management would not address the potentially significant problem of ocean acidification to marine ecosystems.

4.25.3 Adaptation

The majority of both natural and human systems will have to adapt to climate change in some form or the other. A broad array of adaptation strategies has been proposed for reducing the impacts of climate change in both more natural systems and human communities (IPCC 2007a; Heller and Zavaleta 2009) (Table 2). Many of these strategies are either general concepts or strategies that apply to most ecosystems and regions. We begin by describing general concepts and strategies. We then describe some of the strategies that have been proposed for four broad types of ecosystems including freshwater, terrestrial, coastal, and human-dominated systems. For the freshwater, terrestrial, and coastal systems, we focus on strategies that would lessen negative impacts of changing climate on ecosystem functioning and ecosystem services. For the human-dominated systems, we discuss the ways that some of the most often discussed strategies for climate adaptation in these systems will impact (either negatively or positively) ecosystem functioning and the provision of ecosystem services in these and in surrounding areas.

4.25.3.1 General Concepts and Strategies

4.25.3.1.1 Spatial and Temporal Scale

Developing adaptation strategies to address future shifts in climate will require expanding the temporal and spatial scales of plans, policies, and management (Kareiva et al. 2008; Lawler et al. 2010). Three-year, 5-year, and even 10-year plans will fail to address many climate impacts. Future planning will need to address both short-term and long-term changes in systems. To address long-term changes, plans and policies will need to look at least 20 years into the future and will be more useful if they look ahead 50 or more years for many ecosystems and ecosystem services. It will often also be necessary to expand the spatial scale at which systems are managed and policies and plans are developed. As species move and ecosystems change, it will be necessary to think well beyond neighborhood, park, refuge, state, or even national boundaries. Planning will need to occur at multiple, integrated scales and will need to involve local, regional, and sometimes national participants (Kareiva et al. 2008).

4.25.3.1.2 Environmental Justice

While expanding the temporal and spatial scale of climate adaptation strategies, it will be necessary to keep in view local histories, politics, and economies. Scale and locality also play a formative role for issues of ‘environmental’ or ‘climate’ justice. Environmental justice describes the tendency for poor communities to be more vulnerable to environmental degradation. Poor communities tend to bear not only the unequal burden of polluting, destructive, and destabilizing industries but also a disproportionate share of the blame for environmental destruction and responsibility for ameliorating environmental change. For example, polluting industries are often located in poor communities due to cheap land values and the inability of poor communities to politically resist their presence, or a desire to develop jobs at any cost. For instance, swidden agriculturalists in Southeast Asia have been blamed for forest fires despite satellite data pinning large fires to government-sponsored oil palm plantations (Harwell 2000) and Southeast Asian fishers living near toxic riparian runoff from mining have been blamed for polluting local waters by cyanide fishing (Lowe 2006).

4.25.3.1.3 Coordination and Cooperation

The broad spatial scales that are required to address the effects of a changing climate necessitate cooperation and coordination among managers, planners, and policy makers from different jurisdictions, agencies, and management units (Kareiva et al. 2008). They require agencies with diverse mandates and cultures to work together in ways that they have not done in the past. As an example, the US Climate Change Science Program is a federal organization that reaches across federal agencies. The broad scale of climate impacts also requires cooperation across sectors of society and different types of organizations including nongovernmental organizations, local and regional governments, citizen groups, and industry. The US Fish and Wildlife Service’s Landscape Conservation Cooperatives are an example of a system designed to bring together diverse groups of scientists, stakeholders, policy makers, and managers to, in part, address climate change. In addition, as emissions from one locale affect the climate in other locales, addressing the global nature of climate change will involve cooperation at an international level (Hannah 2010). Although, as the above examples demonstrate, some regional, national, and international efforts have been put in place to foster collaboration, more such efforts will need to be made to adequately address climate change.

In addition to cooperation among scientific and political leaders, local and regional stakeholders need to work together as a unified force for social and environmental change. Representatives from the Global North need to appreciate perspectives emanating from the Global South and vice versa. Climate adaptation can be brought into many other environmental and social justice agendas among community advocacy groups and should not remain the purview of the community of knowledge leaders with scientific expertise.

4.25.3.1.4 Resistance, Resilience, and Transition

There are three fundamental approaches to managing systems in a changing climate – promoting resistance, resilience, and transition. Resistance-based adaptation strategies focus on maintaining the current state of a system in the face of climate change or climate-driven changes in the environment. Building a seawall to prevent erosion as sea levels rise and storm surges intensify is an example of a resistance-based adaptation strategy. Resilience can be defined as the ability of a species or system to return to its current state following a perturbation (e.g., Holling 1973). Resilient systems will be able to maintain ecosystem functions and processes and avoid a transition to a new state as climates change. Most of the discussion of climate adaptation to date has focused on managing ecosystems for resistance or resilience. Most of the general adaptation strategies discussed below and the more specific strategies discussed for each of the four types of ecosystems are intended to increase resilience.

The magnitude and rate of projected climatic changes over the coming century will likely make both resistance- and resilience-based strategies insufficient or ineffective in the long run. Managing many systems will require promoting change to a new state. Strategies for promoting change in human-dominated systems may include planting new crops, redesigning road networks, and relocating people. Strategies for fostering change in more natural systems include assisted colonization of threatened plants and animals (see below) and shifting management efforts from one species to another. The outcomes of these more aggressive and forward-looking strategies will be more uncertain, and their implementation will be more controversial. Change is especially hard in social contexts where it is uncomfortable, disadvantageous, expensive, or where the old system is remunerative or beneficial to elites, decision makers, or other small influential groups.

4.25.3.1.5 Adaptive Management

Adaptive management is a flexible approach to managing a system in which the management actions are treated as large-scale experiments (Holling 1978; Walters and Hilborn 1978). It is an iterative process in which the system is monitored following the initial management action and new actions (again treated as experiments) are designed and implemented in response to the results of the initial actions. Adaptive management was conceived for managing highly uncertain systems, and thus it has great potential for managing systems in a changing climate (Arvai et al. 2006). Adaptive management approaches designed to address climate change will likely have four basic steps (Kareiva et al. 2008): (1) assessing the potential impacts of climate change on the system in question, (2) designing management actions – in the form of experiments with testable hypotheses or predictions – to address the potential impacts, (3) monitoring the system for climatic changes and system responses, and (4) using the results of the monitoring to evaluate the effectiveness of the management actions and redesign them as necessary before repeating the four steps.

4.25.3.1.6 Increasing Diversity and Reducing Threats

It is generally accepted that more diverse systems are more resilient to environmental change than less diverse systems. Thus, restoring or protecting the biological diversity of a system will likely increase resilience of that system to climate change (Glick et al. 2009). This diversity can be in the form of species diversity, environmental diversity, or genetic diversity (Schindler et al. 2010). A second, general approach to increasing resilience of species and systems involves reducing the impacts of other factors that reduce the overall resilience of the species or system. For individual species, this might mean reducing harvest, restoring or protecting habitat, eliminating diseases, or reducing human interactions. For ecosystems, this may mean reducing pollutants, restoring vegetation, reducing human use, and controlling invasive species.

4.25.3.1.7 Assisted Colonization

As climates change, many species need to move to track suitable climatic conditions and changing habitats. In some cases, it may be possible to facilitate movement by increasing connectivity of freshwater and terrestrial landscapes (see Sections 4.25.3.2 Freshwater Systems and 4.25.3.3 Terrestrial Systems). However, many species with limited dispersal abilities or that face significant barriers to dispersal will be unable to respond to changing climates. Assisted colonization is one strategy that has been proposed for facilitating climate-driven range shifts (Hunter 2007; McLachlan et al. 2007); also referred to as managed relocation and assisted migration – assisted colonization is the translocation of species outside their native range to facilitate movement in response to climate change. The concept is controversial for both ethical and ecological reasons. Some researchers have highlighted the potential for negative, ecological, evolutionary, and economic impacts, as well as ethical concerns (Ricciardi and Simberloff 2009; Sax et al. 2009). Advocates argue that assisted colonization will be essential for cases in which species will have to move to find suitable environments but will be unable to do so, that many of the potential risks are overblown, and that guidance can be developed for the strategic and informed use of assisted colonization. Several decision-making frameworks and prioritization strategies for applying assisted colonization have been proposed (Hoegh-Guldberg et al. 2008; Richardson et al. 2009). Although assisted colonization will likely be a useful strategy in many systems, there will be specific factors and risks that will need to be considered for particular systems (e.g., in freshwater systems, Olden et al. 2011).

4.25.3.2 Freshwater Systems

Virtually all freshwater systems are already impacted by human activities (e.g., Vörösmarty et al. 2010). Under current climate projections, virtually all freshwater ecosystems will face significant impacts by the middle of this century. Most of these impacts will be detrimental from the perspective of existing freshwater ecosystems and the human livelihoods and communities that depend upon them (Poff et al. 2002). Discussions have broadly focused on rising water and air temperatures, increasing and decreasing precipitation, increasing evapotranspiration, and changing regimes of groundwater and surface runoff. There are four basic types of adaptation strategies that have been proposed for addressing these impending impacts. We define these as ecological water management, connectivity, protected areas, and restoration strategies. Below, we briefly describe some of the specific strategies that have been proposed in each of these areas.

4.25.3.2.1 Ecological Water Management

Increased water scarcity associated with decreased precipitation and increased warming in some regions is likely to prompt the modification of dams and reservoirs to improve storage capacity (see Section 4.25.3.5.3 Managed Aquatic Systems). Traditional water management has generally sought to dampen the natural variability of river flows to attain steady and dependable water supplies for domestic and industrial uses, irrigation, navigation, and hydropower, and to moderate extreme water conditions such as floods and droughts (Postel and Richter 2003). However, the extraordinary species richness and productivity characteristic of freshwater ecosystems is strongly dependent upon, and attributable to, the natural variability of their hydrologic conditions. Thus, large changes to natural flow regimes can have large impacts on species, ecosystems, and society (Postel and Carpenter 1997; IUCN 2000; WCD 2000).

The water needs of humans and natural ecosystems are commonly viewed as competing. However, water managers and political leaders increasingly recognize that there are limits to the amount of water that can be withdrawn from freshwater systems before their natural functioning and productivity, native species, and the array of goods and services they provide are severely degraded (Richter et al. 2003). This has led to a growing realization that society derives substantial benefits both from out-of-stream extractions of water as well as by maintaining adequate flows of water within freshwater ecosystems. In recent years, the water needs of river ecosystems are receiving increasing attention in water-supply planning, offering hope that many rivers can be protected before their health and ability to provide important goods and services is seriously compromised by water development.

Restoring or protecting some semblance of the natural river flow conditions necessary to support ecosystem function (called environmental flows) into the future is one of the most important climate change adaptation strategies for flowing waters. Recent regulatory mandates and policy decisions calling for restoring and preserving environmental flows have led to a reexamination of dam operations for better protection of river health (Watts et al. 2011). For example, the South African National Water Act (1998) calls for the creation of a reserve of water in each river basin to meet both basic human needs and protect river ecosystem health. Similarly, other national directives and international agreements such as the Water Framework Directive of the European Union are providing mechanisms for river protection, including the provision of adequate environmental flows (Postel and Richter 2003).

Maintenance of environmental flows (flows that sustain river ecosystems) is likely to be the highest priority adaptation response for freshwater ecosystems in most contexts. This will require policies and implementation mechanisms to protect (and, if necessary, restore) flows now, and to continue to provide environmental flow regimes under changing patterns of runoff associated with climate change.

4.25.3.2.2 Connectivity

As air and water temperatures warm, many freshwater species will be forced to rapidly adapt to their new environments, to migrate to more suitable habitats, or face extinction (Heino et al. 2009). Responses of aquatic organisms to climate change will be constrained because they are limited to dispersal along pathways of connected water. Consequently, the linear nature of river systems makes them highly prone to fragmentation from waterfalls, dams, and water withdrawals. Such fragmentation can not only limit dispersal and the ability of species to track climate change but also disrupt the completion of life cycles for many freshwater organisms. For many streams, especially in arid and semiarid ecosystems, there is concern that more frequent and severe droughts will lead to the building of more dams and water diversions, further fragmenting stream networks (Seager et al. 2007).

Increasing the connectivity of freshwater systems is one key way to help aquatic systems adapt to climate change. Species responses to climate change will be limited by human-engineered structures, including hundreds of thousands of dams, diversions, and impassable road culverts that exist globally (Nilsson and Schopfhauser 1995). In the United States alone, there are over 80 000 large dams and an estimated 2.5 million or more small impoundments that disrupt the dispersal of aquatic organisms. In recent decades, however, new water laws and programs have helped to increase habitat connectivity by removing or modifying human barriers to movement in river systems. Increasingly, small dams and diversions are being removed for a number of ecological, social, and economic reasons, including the enhancement of longitudinal connectivity for fish migration (Stanley and Doyle 2003). Similarly, temporary barriers such as impassable culverts under roadways are being modified to allow for easier recolonization and movement of fishes (Roni et al. 2008). Although this management strategy may promote the adaptive capacity of species to respond to climate change, the removal of such obstructions can simultaneously increase the risk of invasion by nonnative species and associated diseases, which are major threats to ecosystem structure and function. In fact, the conversion of culverts into permanent barriers has been a common management approach to protect isolated native populations from invasive species spreading upstream (Fausch et al. 2009). Given the complexities of promoting the movement of native species while concurrently limiting the spread of invasive species, it is unlikely that the removal of barriers to enhance habitat connectivity will be a successful adaptation strategy in all areas for reducing the impacts of climate change on ecosystem function.

4.25.3.2.3 Freshwater Protected Areas

In addition to restoring or protecting environmental flows and increasing connectivity within stream networks, it may be necessary to protect the species themselves to allow them to move through or persist in more intensely managed landscapes. In aquatic ecosystems, this may involve increasing the size of existing reserves or creating new protected areas that encompass important freshwater resources and allow for native species and assemblages to persist into the future (Abell et al. 2007). Such acquisitions and agreements ideally would capture a large portion of the geographical, ecological, and geophysical range of multiple species, thus increasing opportunities for organisms to adapt and evolve to changing environmental conditions. Protected areas have historically been a cornerstone of terrestrial conservation – and are discussed in much more detail in that section, below. Nonetheless, protected areas will likely play a major role in protecting aquatic species as climate change and areas could easily be prioritized to provide protection for both terrestrial and aquatic systems in a changing climate (Abell et al. 2007).

4.25.3.2.4 Restoration of Riparian Vegetation

Projected increases in air temperatures, combined with reduced snowpack, earlier onset of spring peak flows, and lower summer baseflows, will have direct implications for the thermal regimes of streams and rivers (Poff et al. 2002). The ecological implications of stream warming are significant. Water temperature directly influences the metabolic rates, physiology, and life histories of aquatic species and helps determine rates of important ecological processes such as nutrient cycling and productivity. In general, warming will produce a general shift in species distribution poleward with extinctions and extirpations of cold-water species at lower latitudes and range expansion of warm-water (often invasive species) and cool-water species into higher latitudes.

Restoring and protecting riparian vegetation – the trees and shrubs that grow along the banks of rivers and streams – has the potential to reduce stream temperatures in certain places. Recent modeling suggests that riparian habitat restoration can play an important role in offsetting the effects of climate change. Battin et al. (2007) used a series of linked models of climate, land cover, hydrology, and salmon population dynamics to investigate the impacts of altered stream flow and temperature on the effectiveness of proposed habitat restoration efforts designed to recover Chinook salmon populations in the Pacific Northwest of the United States. This study showed that in the absence of habitat restoration, basin-wide spawning populations would decline by an average of 20–40% by 2050. By contrast, they found large increases in juvenile rearing capacity associated with proposed riparian habitat restoration, which limited climate-induced declines to 5% according to one climate model and increased salmon abundance by 19% according to another model. However, the model results showed that not all expected climate impacts could be mitigated entirely. In relatively narrow streams, reforestation was predicted to decrease water temperatures by increasing shading, but in wide, main-stem reaches where most Chinook salmon spawn, riparian vegetation had a minor effect on water temperature. In addition to restoring riparian areas, targeted protection of forested riparian buffers using fencing to stop livestock from entering the stream and trampling/grazing vegetation or conservation easements to eliminate farming activities may also help to reduce stream temperatures.

4.25.3.3 Terrestrial Systems

The many adaptation strategies that have been proposed for addressing climate change in terrestrial systems can be loosely grouped into three categories – those that involve protected lands and conservation planning, those that address connectivity, and those that are more species or site specific in nature.

4.25.3.3.1 Protected Lands and Conservation Planning

Protecting land is arguably one of the most effective ways of conserving biodiversity and terrestrial ecosystem services. It is generally assumed that lands that are selected to protect today's species and ecological systems will protect those species and systems into the future. Climate change brings this assumption into question. As climates change and species distributions shift, species will move into and out of reserves. Changes in species composition, the timing of ecological events, and the rates of ecosystem processes will result in changes in the functioning of ecosystems and the services they provide. Many proposed adaptation strategies address these challenges by augmenting current protected areas with additional reserves, parks, and preserves (Heller and Zavaleta 2009; Lawler 2009). These strategies range from broad calls for more protected lands to more sophisticated recommendations about how to select new lands or design new reserves to better protect biodiversity and ecosystem services as climates change.

A number of strategies have been proposed for determining where to put new protected lands to best address the effects of climate change. Some of the simplest strategies involve placing reserves at the poleward or elevational boundaries of the range limits of specific species (Peters and Darling 1985), at major transitions between vegetation formations (Halpin 1997), or at the core of species environmental distributions (Araújo et al. 2004). Others have proposed placing reserves between existing reserves – in the hopes that those new reserves will act as stepping stones allowing species to better move from reserve to reserve. Yet another recommendation involves placing reserves across strong environmental gradients. Reserves that span many different environments will potentially allow species to shift their distributions without leaving the reserve.

In addition to these simple rules of thumb for placing reserves to address climate change, many more sophisticated approaches to selecting areas for new reserves have been proposed. For example, modeled climate-driven shifts in species distributions can be used to select new reserves that will protect biodiversity today and into the future (Hannah et al. 2007; Vos et al. 2008; Hole et al. 2009). Although this approach may prove useful for some species and systems, care must be taken in the use of the models developed to project species range shifts. There are many uncertainties associated with the models themselves and the climate projections on which they rely. Another proposed approach to building a reserve network that will be resilient to climate change involves protecting environments in lieu of protecting species and systems. This approach has been referred to as 'protecting the ecological stage.' This analogy implies that the species and the ecological systems are players and that the soils and topography of a region form the stage on which they interact and evolve. By protecting a suite of diverse environments, it is assumed that one will protect the areas where new ecological systems can develop as climates change (Anderson and Ferree 2010; Beier and Brost 2010). Similarly, others have suggested that more resilient reserve networks will be those that include a diversity of current climates (Pyke and Fischer 2005). Although climates will change, many of the climate gradients generated by latitudinal and topographic patterns will remain. Thus, a set of reserves that protects a diversity of climates today will likely protect a diversity of climates in the future. At least one recent study has applied the concept of protecting environments (topographies, soils, and climate gradients) to a reserve-selection problem (Schloss et al. 2011). One last approach to building a resilient reserve network in a changing climate involves placing reserves in areas that are likely to serve as climate refugia. Refugia are areas that are projected to experience minimal climatic changes and/or have cooler microclimates (Saxon et al. 2005; Hansen et al. 2010; Shoo et al. 2011).

One potential opportunity for climate change adaptation is to consider people as an essential component of species conservation and climate adaptation. While reserve and park systems have a long history of alienating local people, using violence and other coercive measures to separate people and wildlife, in this case, local livelihoods are also threatened by climate change. This provides an opening for a new approach to conservation and a new discourse on the relationship between local people and wildlife.

4.25.3.3.2 Connectivity

As for freshwater systems, improving the connectivity of the terrestrial landscape will be critical for addressing climate change. In response to historical climatic changes, many species shifted their ranges – moving toward the equator as ice sheets advanced and moving poleward as the ice sheets retreated. Today's species will have a much harder time responding to current and impending climatic changes. Present-day landscapes – unlike the landscapes of the distant past – are fragmented by roads, agricultural fields, and residential development. Given that many species will have trouble moving across these human-dominated landscapes, it will be essential to reconnect fragmented landscapes to allow species to respond to shifting climates. Not surprisingly, improving landscape connectivity was the most often recommended climate change adaptation strategy in a recent review of the literature (Heller and Zavaleta 2009).

Many of the recommendations for increasing connectivity involve designing corridors that connect current protected lands. Traditionally, such corridors have been designed for particular focal species, and they have connected reserves or remaining fragments of habitat. However, corridors that facilitate species ranges shifts and the reshuffling of ecosystems will need to connect what is habitat for a species today with an area that may become habitat in the future. In this way, corridor design will need to evolve to address climate change. One such approach to developing corridors for addressing climate change involves basing the corridors on environmental gradients instead of on the current vegetation (which is often used as a measure of habitat) (Beier and Brost 2010). Another approach uses projected changes in climate to orient corridors (Ackerly et al. 2010). A third method involves using modeled shifts in species distributions to identify potential routes that species would need to take to move from currently suitable climates to places where climates will likely be suitable in the future (Williams et al. 2005; Rose and Burton 2009). These three approaches are based on different assumptions and have different levels of associated uncertainty. In general, the uncertainty increases with the intensity of modeling required to identify the corridor, and thus the first of the three approaches has the least inherent uncertainty and the last of the three has the most.

Although corridors may be useful for some species, they will not be feasible or effective in all places or for all species. In addition to designing corridors to facilitate species movements, it will likely be necessary to improve the permeability of the landscape in general (Franklin and Lindenmayer 2009). Increasing landscape permeability will involve changing the way we use and manage the landscape. Changes in forest harvest practices from clear-cuts to selective, retention harvests can increase the connectivity of forested landscapes. Landscape planning and zoning for residential development can reduce landscape fragmentation. Windbreaks, fencerows, and crop choices can be used to increase the connectivity of agricultural lands. At a finer scale, choices of landscaping plants, road placement, and wildlife over- and underpasses can increase landscape permeability.

4.25.3.3.3 Species- and Ecosystem-Specific Strategies

Protected lands and connectivity increase species ability to adapt to changing climates at relatively large spatial scales. In general, they address species movements. Adaptation strategies are also needed at finer scales. In particular, strategies are needed that address individual species and ecosystems. Many of these finer scale approaches tend to involve reducing temperatures or otherwise offsetting the exposure to the changes in climate or climate-driven changes in environmental conditions. For example, it may be possible to reduce temperatures by restoring vegetation to provide shade (Wilby et al. 1998; Wilby and Perry 2006). It may be possible to reduce the impacts of changing fire regimes through forest management practices. Fire suppression policies, may, for example, have particularly severe ramifications in a climate in which fires will generally be larger and more frequent. It may also be feasible to provide supplemental water for particularly vulnerable plants or animals in times of drought or during heat waves. Similarly, shade shelters could be provided to help some animals weather heat waves in extreme climates. Although some of these strategies may prove useful in the short term, many will be neither cost-effective nor long-term solutions.

Another system-specific approach to addressing climate change involves altering species composition or community structure in a way that allows a system to better cope with climatic changes. For a forested system, this may mean planting new species or planting seeds of the same species that have a different genetic makeup (Millar et al. 2007; Glick et al. 2009). Likewise, for grasslands and shrublands, this may mean choosing different species or strains for restoration purposes. Moreover, it may mean facilitating the transformation of an ecosystem – for example from a shrubland to a woodland or from a shrubland to a grassland. In many cases, the first species to move into these transitioning systems may be invasive species. Facilitating the transition to a new state using species native to the region may, in many cases be preferable to having new systems dominated by invasive species. These extreme cases will require ex situ conservation strategies, including seed banking and captive breeding to ensure the long-term survival of the species.

4.25.3.4 Coastal Systems

The interface between the land, sea, and air found in coastal areas is a high-energy system subject to storms, winds, and tides. It is also where the majority of protein comes from in many regions of the world. Many vital ecosystem services are provided along coastal margins of continents and islands. Fringing coral reefs and mangrove forests buffer wave energy, which reduces erosion along the coast. These systems also provide critical habitat for many species, especially nursery areas for provisional services such as fisheries. In many areas, sea-level rise and associated storm surges will make it difficult to protect these systems and the services they provide. Nonetheless, there are two main approaches that will likely prove most useful in coastal systems: building resilience through protection and restoration and facilitating the transition to new ecosystems.

4.25.3.4.1 Protection and Restoration

One of the more beneficial ways, from both an environmental and economic standpoint, to adapt to predicted changes from climate change is by protecting and restoring natural systems that provide multiple ecosystems services. This would include protection of human infrastructure from sea-level rise and increased inundation. Protection and restoration of natural buffers such as barrier islands, mangroves, and coral reefs not only require little financial construction and maintenance but also maintain the wealth of ecosystem services associated with these systems, which include nursery and rearing habitat for many commercial seafood stocks such as fish and shrimp, recreational and cultural opportunities for humans, and protection from inundation. Some natural protection features such as sea ice cannot be maintained in the face of increasing temperatures. In Alaska, the loss of sea ice and melting of permafrost due to warming ocean and air temperatures has exposed the shore to wave energy that used to be absorbed or damped by sea ice or frozen soils. Undoubtedly, ecosystem services that depended on that sea ice protection have also been lost.

Many regions have seen a huge decrease in the area covered by mangroves as coastal areas are drained and mangroves removed for aquaculture. Worldwide, it is estimated that more than 50% of mangrove forests have been destroyed or converted to other uses. On a local scale, many areas have lost all of their mangroves. This loss destroys a wide range of ecosystem services provided by these forests, which range from carbon sequestration to flood protection, spawning, and rearing grounds for many fish and other marine species. Restoring mangrove forests results in increased storm surge protection for natural and human coastal systems, provides nursery habitat for many commercially important fisheries, and stores sediments that may damage offshore coral reefs.

Worldwide, corals exhibit well-documented environmental adaptability over time scales of weeks to thousands of years.

Corals are actually two creatures that live together in a symbiotic relationship. Zooxanthellae are the algal component of corals that provide nutrients generated from photosynthesis to the animal component. Different zooxanthellae species and different species of corals in general have differential environmental tolerances. For example, some corals near the Arabian Peninsula exist under conditions of salinity and temperature that are greater than near-term predicted future average salinities and temperatures resulting from climate change. These adaptive changes likely operate on a decadal time scale. Thus, in some cases, it may be possible to identify particular species or zooxanthellae and algal combinations that are more resilient to warming. Protecting coral reefs from other stressors such as excess sediment and/or nutrient and pollutant inputs from terrestrial sources and unregulated diving can increase the coral's ability to adapt to increased water temperatures. Technological adaptation measures include using sprinklers to create roughened sea surface to decrease light penetration or covering reefs with shade cloth to limit bleaching of corals.

4.25.3.4.2 Transition and Migration

As sea levels rise, many coastal systems will need to migrate inland. When there are extensive human uses of coastal space or urban buildup, space for ecosystem recovery and migration of species will not be available. Providing space for the migration of biotic elements of the coastal system at the same time as when human populations are forced to move would provide cobenefits for coastal life and human communities. Ecosystems will usually adjust to changing salinities and water levels, and the services provided by the system will be maintained where conditions are suitable. For example, in 1996, a subdivision east of Houston in Baytown, Texas, was bought out, the structures removed, and the entire area restored to coastal wetlands. A more extreme example of planned retreat is the Maldive Islands. Their current plan is to exploit the current coastal amenities, primarily beaches and coral reefs; secure capital with which to train younger citizens; and prepare them for relocation to other countries such as India, Sri Lanka, and Australia. In the short term, there are negative consequences to ecosystem services due to commercial and touristic exploitation, but in the long run, by abandoning the islands, the system will be able to come to a new ecological state.

In some cases, removing human infrastructure will be a necessary but insufficient means of fostering landward shifts in coastal systems. In such cases, it may be necessary to facilitate the shift in natural systems and stabilize soils by planting more coastal species inland as water levels rise. Such actions have been taken as part of the Alligator River climate change adaptation project on the North Carolina coast in the southeastern United States (Pearsall 2005, Pearsall and Poulter 2005).

4.25.3.5 Human-Dominated Systems

Here we describe some of the adaptation strategies that have been proposed for built environments, agricultural systems, and managed freshwater systems. We explicitly focus on how the most commonly proposed strategies could affect associated ecosystems.

4.25.3.5.1 Built Environments

The severity of climate change impacts will depend, in large part, on our ability to transform the built environment in response to changing conditions. The following section discusses some of the climate change adaptation strategies that will likely take place in built environments and the effects that these strategies may have on ecosystem functions and services. We briefly discuss human migrations, flood control, sea-level rise, increased water storage, and urban heat-island effects.

Perhaps the most basic form of climate change adaptation involving the built environment is human migration. Vulnerable populations will be forced to abandon their homes, relocate, and rebuild. They will displace resident populations and open up the possibility of conflict in the process. The bulk of climate change-related human migration that is already occurring involves movement from rural areas to cities in developing countries. Unplanned urban growth will fuel the expansion of informal urban settlements, and by 2050, 3×10^9 people, one-third of the world's population, may inhabit urban slums. In both rural and urban environments, proactive planning and resettlement strategies that identify populations at risk and relocate them stand to drastically reduce long-term human hardship stemming from climate change. They can also protect vital ecosystems from the degradation associated with unplanned development. However, resettlement can have profound negative impacts. Poorly executed, it can degrade indigenous culture, undermine traditional livelihoods, destroy social networks, and deepen poverty by distancing poor communities from employment opportunities. Given these dangers, in some cases, it is preferable to fortify communities against climate change impacts in place. This approach introduces improvements to infrastructure and housing, builds upon the prior efforts of communities, and preserves social networks.

In many regions, climate change will result in increased rainfall and flooding. Conventional approaches to storm water management rely on defensive hard structures. Water runs from impermeable concrete and asphalt surfaces into storm drains, culverts, and concrete embankments. Rivers are straightened, channelized, and isolated from their natural floodplains to accommodate human settlement. As flood events become more intense and frequent with climate change, storm water management strategies must evolve. Rather than take a defensive stance, they should promote the coexistence of humans, habitat, and water. Soft infrastructure or low-impact development strategies, such as permeable paving, green roofs, green walls, rain gardens, bioswales, and constructed wetlands offer a promising alternative to conventional storm water infrastructure. They promote groundwater recharge, reduce flooding, and improve water quality with downstream benefits to aquatic habitats. In areas of severe flood risk, resettling residents on higher ground and reintroducing rivers to their floodplains protects human populations, dissipates flood energy, and creates wetland habitat. Through temporal land-use practices such as intermittent farming, floods become an asset rather than a threat, depositing sediments that enrich agricultural lands.

By 2050, rising sea levels may displace as many as 162 million people (Myers 2002). Like conventional storm water infrastructure, conventional seawall infrastructure relies on defensive hard structures. As sea levels rise, existing levees will become obsolete. Here again, soft-infrastructure strategies offer a promising alternative. Graduated transitions from sea to land including manmade offshore islands, expansive shallows, and coastal marshes act as buffers for storm surge better equipped to absorb the impacts of extreme weather events. They provide habitat for marine species and, in coastal cities, public space for recreation when conditions permit.

In places like coastal Peru and sub-Saharan Africa, disappearing glaciers and reduced precipitation will increase the frequency, duration, and impacts of drought, undermining food and water security. A number of interventions in the built environment can help communities cope with water scarcity. Increasing water storage at scales ranging from dams to urban reservoirs and household rainwater barrels helps bolster water supplies during prolonged dry periods. In coastal areas, desalination plants and, in select localities of South America and Africa, fog harvesting may prove to be viable alternative water sources. Ecological sanitation technologies such as dry toilets and gray water wetlands conserve potable water for drinking and, as part of a network of integrated ecological infrastructure systems, irrigate and provide nutrients for urban farms and forests. They also help prevent contamination of local water bodies, preserving their viability as sources of potable water and ecological integrity. Further impacts of, and opportunities associated with, these various adaptation strategies are discussed in the Sections 4.25.3.5.2 and 4.25.3.5.3.

Cities in developed countries are on average 1–3 °C hotter than the surrounding countryside (UN Human Settlements Programme 2011). Higher urban temperatures increase energy use, degrade urban air quality, raise the temperature of urban storm water runoff, and contribute to general discomfort, respiratory illnesses, heat stroke, and other heat-related illnesses. Warming in conjunction with increased urbanization will amplify urban heat-island effects and their associated impacts.

Several strategies can help reduce urban temperatures. At the scale of the site, urban trees with high, dense canopies, strategically planted around buildings, in parking lots, and along streets permit the passage of air, shade heat-absorbing surfaces, and cool the atmosphere through evapotranspiration. They also reduce the temperature of runoff water. Green roofs perform a similar function on roof surfaces. Buildings and landscapes constructed from materials with high solar reflectance or albedo absorb less heat and reduce urban temperatures. At a larger scale, streets oriented parallel (or up to 30°) to prevailing winds, permeable networks of public open space, strategically situated low-rise buildings, and gaps between high-rise structures increase the air permeability of urban environments.

4.25.3.5.2 Agricultural Systems

Increased temperatures and changes in precipitation regimes are likely to have negative impacts on global food security by worsening the existing regional disparities between developing and developed countries (Easterling et al. 2007; Rosenzweig and Tubiello 2007). This is supported by the prediction that a moderate warming accompanied with elevated CO_2 concentrations is likely to lead to an increase in crop productivity of developed countries in temperate mid and high latitudes, whereas even a slight increase in temperature could damage crops that are already growing at supraoptimal temperatures in countries located in tropical, low latitudes (Easterling et al. 2007; Easterling 2010). As in other systems, even with significant mitigation efforts, adaptation strategies will be necessary to address the impacts of climate change on agriculture.

Adaptation strategies for more resilient agricultural systems may include altering the timing and location of cropping, switching crop species and cultivars, selecting livestock breeds, crop rotations, and efficiently using and managing water resources. These types of adaptation strategies have been referred to as autonomous strategies (Easterling 2010). Implementing some of these strategies, such as changing the type of livestock that is grazed or changing crop rotations could have profound effects on ecosystem functioning. However, in general, these types of adaptation strategies will have environmental impacts smaller than more intensive strategies that are designed to transform systems.

For many agricultural systems, the magnitude of climatic changes will necessitate more intensive planned adaptation strategies that foster significant transformations of systems or infrastructures (Easterling 2010). Such intensive strategies will be particularly important for sub-Saharan Africa and South Asia where climate will have major impacts on agriculture (Lobell et al. 2008; Nelson et al. 2009). These planned adaptation options include developing new infrastructure (e.g., irrigation infrastructure, transport and storage infrastructure, and efficient water use and reuse technologies), investing in new technical and management options (e.g., crop and livestock improvement, enhancing germplasm), shifts in the distribution of agriculture (e.g., abandoning some areas and farming new lands), and building the capacity to make continuing adjustments. Here, we discuss two of these strategies – improving crop performance and water conservation – in more detail.

Stresses on crops due to extreme heat and pest and pathogen pressures are likely to increase with climate change (Deutsch et al. 2008; Battisti and Naylor 2009). Multiple adaptation options are available for improving crop performance in the face of such climate-driven stresses. First, in conjunction with conventional breeding, crop improvement through genetic engineering is seen as an effective adaptation tool in a changing climate – although public opinion is often divided on the use and consequences of genetically engineered crops (MacDiarmid 2007; Jones 2011). A second approach involves maintaining crop genetic diversity by, for example, collecting and storing the diversity of current cultivars or local landraces. A third adaptation strategy involves exploiting symbiotic relationships between crops and other organisms. For example, it has been shown that numerous fungal and bacterial endophytes confer stress tolerance to heat, drought, salinity, and pathogen attacks (Rodriguez et al. 2008; Rodriguez et al. 2009), and others promote growth and fix atmospheric nitrogen (Doty et al. 2009; Xin et al. 2009). Other strategies include the application of kaolin particle films to reduce heat stress and photoinhibition and to mitigate pest damage (Glenn et al. 1999; Glenn 2009) as well as the incorporation of biochar into soils to confer numerous agronomic benefits that enhance crop performance and stress tolerance (Marris 2006).

Irrigated agriculture accounts for about 70% of the world's freshwater withdrawals (Rosegrant et al. 2009). With increasing global population, the demand for irrigated agriculture will continue to increase globally because realized crop yields normally increase considerably with irrigation. Adaptation strategies that foster more efficient use of water in agriculture will be critical for achieving global food security while conserving water in a changing climate. These strategies will include institutional water management reform, economic incentives for efficient water use, and infrastructure investment for efficient irrigation and water delivery systems (Rosegrant et al. 2009). The 'virtual water' trade through crop products from water-abundant to water-deficit areas should be considered as one of the key adaptation options to climate change (Rosegrant et al. 2009; Easterling 2010). Improving crops for higher water-use efficiency (i.e., greater yield with less water use) should be a goal for genetic, ecological, and agronomic options of adaptation discussed above. Alternative strategies of increasing water storage capacity with dams and increasing the number of stream diversions for agriculture will, in contrast, have significant impacts on aquatic ecosystems (see the Section 4.25.3.5.3 Managed Aquatic Systems).

4.25.3.5.3 Managed Aquatic Systems

As discussed above, changes in temperature and precipitation are likely to lead to changes in the demand for water. Projected climatic changes will likely lead to increased demands for residential use, irrigated agriculture, hydropower production, and carbon capture and storage technologies. In some regions, current water management may not adequately cope with the impacts of changing precipitation regimes and increased evaporation on the reliability of water supply, flood risk, health, agriculture, energy generation, and freshwater ecosystems (Palmer 2008). Adaptation strategies designed to address water management for human uses will either directly or indirectly affect ecosystem functioning and ecosystem services. In addition to the adaptation strategies for addressing water demands for agriculture and residential use (addressed to some extent in Sections 4.25.3.5.1 and 4.25.3.5.2), other important adaptation strategies for managed aquatic systems that will impact ecosystem functions and services include increased extraction of groundwater, improving storage capacity by building or modifying dams and reservoirs, desalination of seawater, and expansion of rainwater storage and water transfer (Bates et al. 2008; Hirji and Davis 2009).

Improving storage capacity by building or modifying dams and reservoirs is likely to be one of the most common regional responses to decreased water availability and increased demand for water. The great utility of running water has resulted in the extensive exploitation of streams and rivers by humans throughout the world, a process greatly facilitated by the construction of hundreds of thousands of dams globally (Nilsson et al. 2005). By capturing high river flows and releasing the water in a carefully controlled manner, dam managers can deliver steady and dependable water supplies to downstream areas, protect settlements from floods, or generate power. Although human manipulation of the world's river flows has provided many societal benefits, it has also caused considerable ecological damage and the loss of important ecosystem services valued by society (Baron et al. 2002). Flow regulation for hydropower and storage, diversion for human use, and extraction of groundwater connected to stream systems often significantly affect the natural seasonal and interannual variation in river flow, commonly referred to as the natural flow regime (Poff et al. 1997). A natural flow regime is needed to sustain the complex riverine and riparian ecological functions and processes that support native biodiversity and provide myriad ecological services including maintaining water quality, recharging groundwater, and nutrient cycling (Naiman et al. 2002).

Facing an ominous future of increasingly severe water-supply shortages in many areas of the world, social planners and government leaders are exploring strategies for ensuring that enough water of sufficient quality is available for use by future generations. Human demands for water are expected to increase under a warmer climate, exacerbating current management problems. Increasing demands for irrigation and industrial cooling water could conflict with the increasing demands for municipal water supplies resulting from urban growth. Climate-induced changes to water availability and increasing human demand for water are likely to prompt the construction or modification of dams and reservoirs to improve storage capacity and enhance water security (WCD 2000; Palmer 2008). For instance, by storing water in reservoirs, water managers capture high flows during wet years or seasons to supplement water supplies at drier times, thereby maximizing the reliability of water supplies and certain economic benefits each year. For regions where increases in runoff variability or more prolonged drought conditions are associated with climate change, the pressure to build water-supply reservoirs will be great.

Although the construction of additional dams and reservoirs will undoubtedly provide many societal benefits, a rich body of scientific knowledge has shown that river regulation also causes considerable ecological damage and the loss of important ecosystem services valued by society (Baron et al. 2002; Postel and Richter 2003). River ecosystem health deteriorates when natural flows of water, sediments, and organic materials through a river system are substantially disrupted or modified by human activities (Poff et al. 1997; Richter et al. 2003). River damming and associated environmental alteration is now widely recognized as a leading cause of declines in freshwater biodiversity globally (Bunn and Arthington 2002). Dams have also been implicated in the loss of commercial fisheries in many estuaries and coastal areas, and in the degradation of other natural ecosystem products and services worldwide (WCD 2000). In addition, reservoirs increase the loss of water due to evaporation. Finally, as mentioned above, reservoirs emit substantial quantities of carbon dioxide and methane into the atmosphere (St. Louis et al. 2000), and therefore, the creation of additional reservoirs is likely to further promote climate change.

In many regions, impending water shortages will also lead to greater interest in desalination as a technique for tapping into the vast and infinitely tempting water supplies of the sea. Recent improvements in reverse osmosis technology, coupled with the rising cost and increasing unreliability of traditional water supplies both currently and projected in the future, are making desalination a water-supply option with major plants in operation, in planning, or under consideration in Europe, North Africa, North America, Australia, China, and India. Like most large-scale industrial processes, making water has a number of actual or potential impacts on aquatic goods and services (WWF 2007). Emerging issues include significant cost and pollution emitted by desalination plants and the mostly unknown, but potentially substantially, effects on freshwater and coastal ecosystems. Intake pipes can remove larvae and small marine organisms, and discharge from desalination plants can elevate levels of salt and other constituents of seawater such as boron; dead sea life, which consumes oxygen while decomposing; chemicals added to change the composition of the water for processing, as well as reducing contamination and clogging of filters and membranes; corrosion by-products; and the heat added for or during processing. Finally, water manufacturing is an energy-intensive process.

4.25.4 Social Considerations in Planning for Mitigation and Adaptation to Climate Change

Although increasing GHG concentrations and the resulting increasing temperatures are global phenomena, the globe will often be an inappropriate scale for developing mitigation and adaptation strategies. Human activities generate differential risks and vulnerabilities that vary with location due to differences in social, political, cultural, and economic conditions (Beck 1992). Although, in one sense, all people are vulnerable to catastrophic climate change, at another more fundamental level, the risk of climate change impacts (along with blame and responsibility) are unevenly distributed. We can begin to think of the unequal distribution of the vulnerability to climate change as a scale issue.

Mitigation and adaptation strategies can be applied at multiple, and often overlapping, scales. At the finest scale, the development of mitigation strategies will depend on local leadership and the attitudes of local populations and individuals toward climate change. At national and international levels, mitigation efforts will be organized through large and formal programs and institutions (e.g., UN-REDD). Although some adaptation strategies will be national and international in nature, much adaptation will take place at finer scales of communities and regions. A hallmark of climate change as a global phenomenon is that leadership and coordination across local, national, and international scales is important for ameliorating its effects. In turn, coordination across scales will entail understanding local climate risks and local and regional understandings of the causes of climate change and the costs and benefits of different mitigation and adaptation strategies.

The effectiveness of any mitigation or adaptation strategy (building codes, population planning, dietary changes, etc.) depends on its acceptance in local, regional, and national communities. Social impediments to adoption of climate change strategies include ideological outlooks, structural constraints, and cultural barriers. For example, free-market ideologies can impede the ability of governments to invest in alternative energies; agricultural subsidies and corporate monopolies on agricultural inputs may create structural barriers to alternative agriculture; and cultural norms for relative water and energy use, family size, or the flavor and texture of food can inhibit conservation of resources and changes in diet.

There is a clear disparity between societies that have contributed the most to GHG emissions and those that will likely suffer the direst consequences of climate change. At the international level, efforts to shift blame from the activities of the rich to the actions of the poor have been used to shirk the responsibility to mitigate climate change and to impede the development of global mitigation strategies. The dispute between the Global North and South over who caused climate change and who must now take responsibility for mitigation is by now well known. Countries in the Global South argue that northern countries have already developed their economies relying on fossil fuel consumption and now, when it is their turn to develop, they are asked to put restrictions on their energy consumption and natural resource use. Meanwhile, the United States has used the reluctance of developing countries to cap emissions as an excuse for inaction on its part. Mitigation and adaptation activities that do not take globally inequalities in wealth, resources, and adaptive capacity into account, or insist on 'equality' in action in a demonstrably unequal world cannot be effective.

Addressing population growth clearly plays a key role in both mitigation and adaptation strategies. However, focusing on population size while ignoring global patterns in the consumption of resources and the distribution of wealth will result in failed policies and strategies. The world's human population is approaching 7×10^9, and a growing population inevitably means greater demand for the numerous goods and services supported by terrestrial and aquatic ecosystems. While the availability of resources has seemingly stretched beyond the direst predictions of several decades ago, the crisis of over-consumption – namely, of coal and other fossil fuels that produce GHGs and contribute to climate change – is simultaneously becoming clearer. While trends over the past several decades suggest that population growth is a significant driver of CO_2 emissions (Bongaarts 1992; Dietz and Rosa 1997), it is also true that urbanization, aging, and changes in household size similarly affect energy use and emissions (MacKeller et al. 1995; Cole and Neumayer 2004). Particular point sources of GHG emissions from energy consumption in developed countries, like the internationally managed oil fields of Nigeria or emissions from the recent Iraq war, which since 2003 has released over 140 million metric tons of carbon dioxide, the equivalent of adding 25 million new cars to American roads (Reisch and Kretzmann 2008), should bear at least as much scrutiny as the desires of third world women and men to bear children. An overarching emphasis on population detracts from a nuanced understanding of the multiple drivers of GHG emissions.

It will be ineffective to focus on the effects of climate change on ecosystems without considering the concurrent effects on human well-being and vice versa. Disparities in climate change risk and human health often overlap, and human health and environmental health are intricately intertwined. Although diseases are often approached as singular phenomena, good models exist that demonstrate the interactive effects of multiple morbidity factors on health outcomes and disease trajectories. For example, interactions between acquired immune deficiency syndrome and tuberculosis, or diabetes and severe acute respiratory syndrome, have synergistic impacts on patients that must be understood together. Likewise, social attributes, like poverty or exposure to racism, interact with disease conditions to increase the damaging effects of disease. Such interactions have the potential to influence the effects of climate change on disease movement and clustering, disease interactions, and the impact of climate change on global health (Baer and Singer 2008). Human action and human vulnerability to such interactions between climate, disease, and the environment are structured by social and economic inequality, and thus mitigation and adaptation strategies will need to take these inequalities into account.

What is clear from a social and political perspective on mitigation and adaptation is that no one set of mitigation or adaptation strategies will be applicable to all people in all places. Suggested approaches to either mitigation or adaptation will involve costs and benefits that are unequally distributed across nations, populations, and societies. There will, for example, always be those who can escape pollution with air filters and private vehicles, use air conditioning to survive heat waves, have access to global food markets and multiple water sources, and those who cannot. The most effective mitigation and adaptation strategies, therefore, will address both climate change and environmental justice.

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Volume 5

Climate Vulnerability

Understanding and Addressing Threats to Essential Resources

Volume 5: Vulnerability of Water Resources to Climate

Editor-in-Chief:
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UNDERSTANDING AND ADDRESSING THREATS TO ESSENTIAL RESOURCES

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VOLUME 5

VULNERABILITY OF WATER RESOURCES TO CLIMATE

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He has served as chairman and member of the AMS Committee on Weather Forecasting and Analysis, and was the chief editor for the Monthly Weather Review for 5 years from 1981 to 1985. In 1977, he received the AMS Leroy Meisinger Award for ‘fundamental contributions to mesoscale meteorology through numerical modeling of the sea breeze and interaction among the mountains, oceans, boundary layer, and the free atmosphere’. He received the 1984 Abell New Faculty Research and Graduate Program Award, and also received the 1987/1988 Abell Research Faculty Award. He was declared ‘Researcher of the Year’ by the Colorado State University Research Foundation in 1993. In 2000, he received the Engineering Dean's Council Award from Colorado State University.

He authored a book published by Academic Press entitled ‘Mesoscale meteorological modeling’ in 1984 with a 2nd edition in 2002, a book for Routledge Press entitled ‘The Hurricane in 1990, a book (coauthored with W.R. Cotton) for Cambridge Press entitled ‘Human impacts on weather and climate in 1995; 2nd ed., 2006, a book (coauthored with R.A. Pielke, Jr.) entitled ‘Hurricanes: Their nature and impacts on society’ published in 1997 by John Wiley and Sons, and was co-chief editor (with R.A. Pielke, Jr.) of a book entitled ‘Storms’ published by Routledge Press in 1999.

He was elected as a fellow of the AMS in 1982 and fellow of the American Geophysical Union in 2004. From 1993—96, he served as editor-in-chief of the US National Science Report to the IUGG (1991—94) for the American Geophysical Union. From January 1996 to December 2000, he served as co-chief editor of the *Journal of Atmospheric Science*. In 1998, he received NOAA's ERL Outstanding Scientific Paper (with Conrad Ziegler and Tsengdar Lee) for a modeling study of the convective dryline. He was designated a Pennsylvania State Centennial Fellow in 1996, and named the Pennsylvania State College of Earth and Mineral Sciences Alumni of the year for 1999 (with Bill Cotton). He is currently serving on the AGU Focus Group on Natural Hazards (August 2009—Present) and the AMS Committee on Planned and Inadvertent Weather Modification (October 2009—Present). He is among one of three faculties and one of four members listed by ISI Highly Cited in Geosciences at Colorado State University and the University of Colorado at Boulder, respectively.

He has published over 370 papers in peer-reviewed journals, 55 chapters in books, coedited 9 books, and made over 700 presentations during his career to date. The listing of papers can be viewed at the project website: http://cires.colorado.edu/science/groups/pielke/pubs/. He also launched a science weblog in 2005 to discuss weather and climate issues. This weblog was named one of the 50 most popular Scienceblogs by Nature Magazine on 5 July 2006 and is located at http://pielkeclimatesci.wordpress.com/.

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Dr Jimmy Adegoke is an award winning climate scientist whose research focuses on understanding the relationships between changing land surface processes and diverse indicators of environmental change. His recent work focuses on societal impacts of environmental change including air pollution studies in rapidly changing midlatitude urban areas and climate impacts on water resources in the Lake Chad Basin. He teaches at the University of Missouri-Kansas City (UMKC) where he served as chair of the Department of Geosciences from 2008—10. From August 2010 until very recently, he was Executive Director of the Council for Scientific and Industrial Research (CSIR) Natural Resources and Environment (NRE) Division, Pretoria, South Africa where he also served as the Director of the Applied Center for Climate and Earth Systems Science (ACCESS), a Center of Excellence (CoE) of the South Africa Department of Science and Technology (DST) Global Change Grand Challenge (GCGC) program. He is a member of several professional societies including the American Geophysical Union (AGU), Association of American Geographers (AAG), and American Meteorological Society (AMS). He is on the advisory council of the African Association for Remote Sensing of the Environment (AARSE) and also serves on the technical advisory committee of several United Nations applied science programs, including the United Nations Educational Scientific and Cultural Organization (UNESCO) crosscutting project on the application of remote sensing for water resources and ecosystem management in Africa. He lives in Kansas city where he served a 3-year team as an appointee of the Mayor of Kansas City Missouri (KCMO) on the city's Environmental Management Commission (EMC).

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Dr Dev Niyogi is an associate professor with joint appointment in the Departments of Agronomy and Earth, Atmospheric, and Planetary Science at Perdue University.

He is also the State Climatologist for Indiana and Director of the Indiana State Climate Office. His research seeks to advance the understanding of vegetation and land surface processes in environmental, weather forecasting, and climate analyses, using a combination of dynamical models and surface, satellite remote sensing, and multiscale analysis products.

His research deals with the understanding and representation of the effects of vegetation – land surface processes in environmental processes at different scales. He is one of the three invited, nonfederal representatives to the community modeling effort of the Weather Research and Forecast (WRF) model working group on Land Surface Models, and to the Federal Geophysical Data Commission (FGDC) Spatial Climate Working Group.

He has authored or coauthored 25 successful proposals for external grants totaling over $3M. He vertically integrates undergraduate, graduate, and postdoctoral researchers in his research and is very interdisciplinary in developing collaborative projects.

Dr George Kallos is a professor at the University of Athens, School of Physics, Division of Environmental Physics and Meteorology. He leads the Atmospheric Modeling and Weather Forecasting Group (AM & WFG). He has a BSc from the University of Athens/School of Mathematics (1975). He obtained his MSc (1983) and PhD (1985) in Geophysical Sciences/Atmospheric Sciences Division, Georgia Institute of Technology, School of Geophysical Sciences, USA. He has 110 publications in peer review scientific journals, more than 230 presentations and publications in conference proceedings publications, 10 contributions in books and more than 200 other publications in subjects related to atmospheric physics and chemistry, sea-state conditions, and renewable energy production. He has been invited 70 times to give talks in conferences, seminars, etc. His published work has received >2000 citations. He has participated in 80 projects. He has organized 12 conferences related to air pollution and dust transport in the Mediterranean. He has supervised 10 PhDs and over 100 MSc theses and participated in 20 PhD examinations in Greece and Europe. He is an associate editor for the journals: '*Environmental Fluid Mechanics*', '*Advances in Meteorology*', '*International Journal of Geosciences*', '*Atmospheric Pollution Research*', and '*Journal of Aerospace Operations*'. He was awarded the International Union of Air Pollution Prevention Association – IUAPPA award for his work on 'Long-range transport and air quality work in the Mediterranean region'. His current research activities are related to atmospheric, climatic, air pollution, and sea-state model development and forecasting. He focuses in fully coupled modeling systems. The latest model developments are related to nucleation processes in clouds, desert dust cycle and its direct and indirect effects. Research activities related to renewable energy resources (wind, ocean, solar) are focusing on high accuracy atmospheric model development, energy relationships and predictions, and protection from extremes.

Timothy Seastedt received his BA in biology from the University of Montana, an MS degree in biological sciences from the University of Alaska at Fairbanks, and a PhD degree from the University of Georgia. He was on the faculty at Kansas State University and is currently a professor of Ecology and Evolutionary Biology and fellow of INSTAAR at the University of Colorado, Boulder. Much of his research has been conducted as part of the Long-Term Ecological Research (LTER) programs at KSU and CU. His interests focus on terrestrial ecosystem ecology and the causes and consequences of biotic change. His recent activities have emphasized the ongoing changes found along the grassland to (melting) glacier gradient that exists in the Colorado Front Range.

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PREFACE

We are pleased to introduce the five-volume set of books on bottom-up, resource-based vulnerability assessments of the societally and environmentally key resources of water, food, energy, human health and well-being, and ecosystem function. This inclusive bottom-up vulnerability concept requires the determination of the major threats to these resources from climate, but also from other social and environmental issues. After these threats are identified for each resource, the relative risk from natural- and human-caused climate change (estimated from global climate model (GCM) projections, as well as the historical, paleorecord, and worst case sequences of events) can be compared with other environmental and social risks in order to adopt the optimal mitigation and adaptation strategies.

The bottom-up, resource-based approach (referred to by O'Brien (2009) as 'contextual vulnerability') that is the focus of the volume is distinct from the Intergovernmental Panel on Climate Change (IPCC) top-down assessment of vulnerability based on the multidecadal GCM predictions (projections) which O'Brien defined as 'outcome vulnerability' (**Table 1** and **Figure 1**).

An excellent example of the contextual vulnerability is the paper by Romero-Lankao et al. (2012) who concluded in a study of the literature that urban vulnerability is dominated by epidemiological studies and top-down assessments, but that inherent urban vulnerability and urban resilience approaches (the contextual vulnerability) are what is required in order to illuminate a more complete set of drivers of urban vulnerability. They also showed that the large majority of papers on vulnerability use the outcome vulnerability approach. However, as discussed below, this top-down approach has major flaws.

First, there is the issue that the term 'climate' has two definitions. The broader view (and the one adopted by NRC (2005)) is that climate consists of the atmosphere, oceans, land, and cryosphere. This is the preferred usage. The second definition is that climate is the term used for the long-term (e.g., multidecadal) statistics of weather.

As reported in the NRC (2005) report and written in the Pielke et al. (2009) article with respect to human climate forcings.

> In addition to greenhouse gas emissions, other first-order human climate forcings are important to understanding the future behavior of Earth's climate. These forcings are spatially heterogeneous and include the effect of aerosols on clouds and associated precipitation [e.g., Rosenfeld et al. 2008], the influence of aerosol deposition (e.g., black carbon (soot) [Flanner et al. 2007] and reactive nitrogen [Galloway et al. 2004]), and the role of changes in land use/land cover [e.g., Takata et al. 2009]. Among their effects is their role in altering atmospheric and ocean circulation features away from what they would be in the natural climate system [NRC 2005]. As with CO_2, the lengths of time that they affect the climate are estimated to be on multidecadal timescales and longer.

and

> "…the natural causes of climate variations and changes are important, as are the human influences. The human climate forcings involve a diverse range of first-order climate forcings, including, but not limited to, the human input of carbon dioxide (CO2). Most, if not all, of these human influences on regional and global climate will continue to be of concern during the coming decades."

Threats from climate involve any one or combination of climate variables as illustrated in **Figure 2**. There do not, of course, have to be changes in the statistics of these variables to constitute a risk. The term

Table 1 Contrast between a top-down versus bottom-up assessment of the vulnerability of resources to climate variability and change

Approach	*Comparative vulnerability*	*Contextual vulnerability*
Assumed dominant stress	Climate, recent greenhouse gas emissions to the atmosphere, ocean temperatures, aerosols, etc.	Multiple stresses: climate (historical climate variability, land use and water use, altered disturbance regimes, invasive species, contaminants/pollutants, habitat loss, etc.)
Usual timeframe of concern	Long-term, doubled CO_2 30–100 years in the future.	Short-term (0–30 years) and long-term research.
Usual scale of concern	Global, sometimes regional. Local scale needs downscaling techniques. However, there is little evidence to suggest that present models provide realistic, accurate, or precise climate scenarios at local or regional scales.	Local, regional, national, and global scales.
Major parameters of concern	Spatially averaged changes in mean temperatures and precipitation in fairly large grid cells with some regional scenarios for drought.	Potential extreme values in multiple parameters (temperature, precipitations, frost-free days) and additional focus on extreme events (floods, fires, droughts, etc.) measures of uncertainty.
Major limitations for developing coping strategies	Focus on single stress limits preparedness for other stresses. Results often show gradual ramping of climate change-limiting preparedness for extreme events. Results represent only a limited subset of all likely future outcomes – usually unidirectional trends. Results are accepted by many scientists, the media, and the public as actual 'predictions'. Lost in the translation of results is that all models of the distant future have unstated (presently unknowable) levels of certainty or probability.	Approach requires detailed data on multiple stresses and their interactions at local, regional, national, and global scales, and many areas lack adequate information. Emphasis on short-term issues may limit preparedness for abrupt "threshold" changes in climate sometime in the short or long term. Requires preparedness for a far greater variation of possible futures, including abrupt changes in any direction – this is probably more realistic, yet difficult.

Adapted from Kabat et al. 2004.

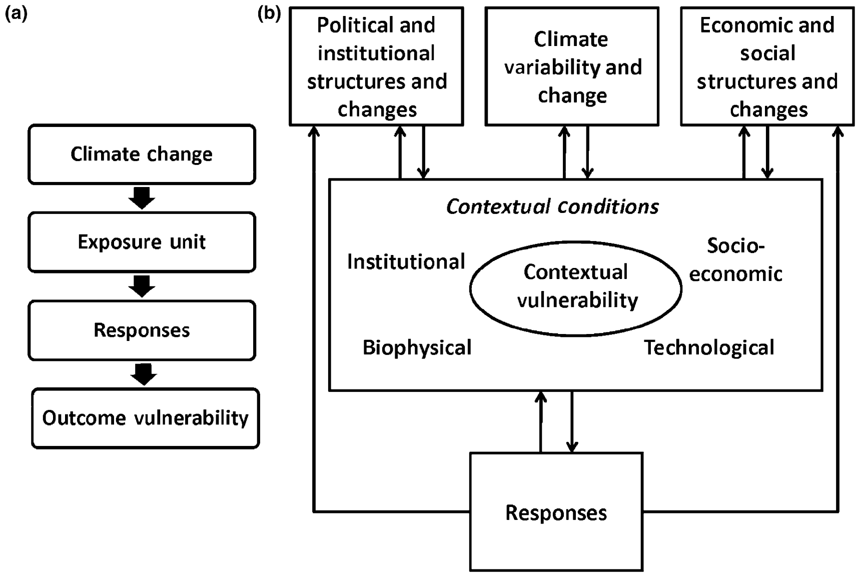
(a)
Climate change
Exposure unit
Responses
Outcome vulnerability
(b)
Political and institutional structures and changes
Climate variability and change
Economic and social structures and changes
Contextual conditions
Institutional
Contextual vulnerability
Socio-economic
Biophysical
Technological
Responses

Figure 1 Framework depicting two interpretations of vulnerability to climate change: (a) outcome vulnerability and (b) contextual vulnerability. *From: Füssel (2009) and O'Brien et al. (2007).*

'climate change' should be used to describe any multidecadal or longer alteration in one or more physical, chemical, and/or biological components of the climate system, but as explained below, this terminology has morphed into multiple, diverse (and often mutually exclusive) definitions as used by the impacts communities.

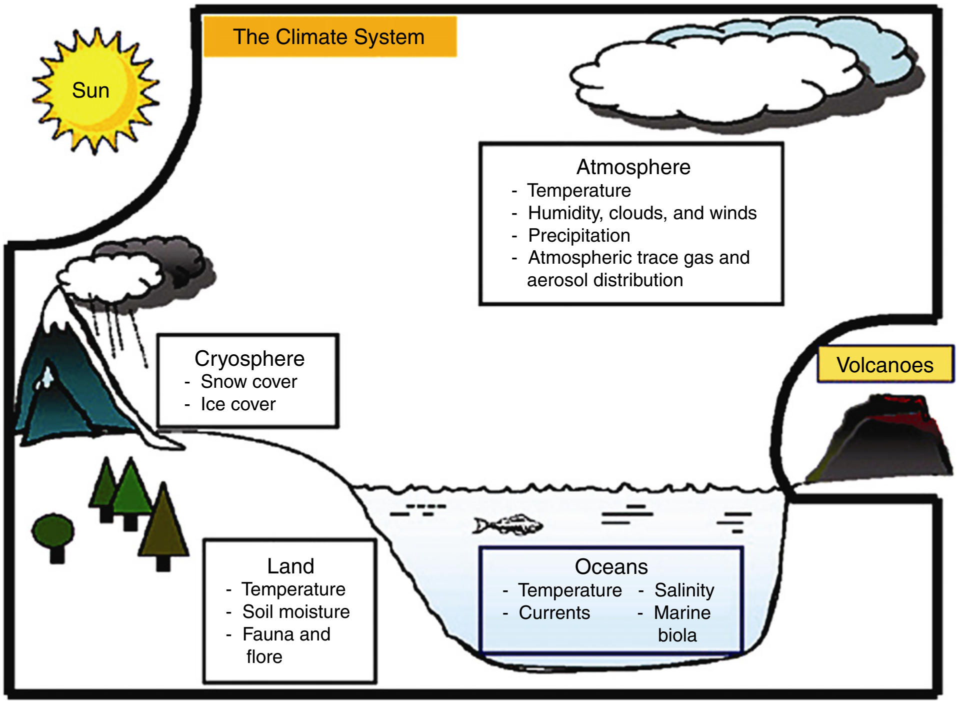
The Climate System
Sun
Atmosphere
- Temperature
- Humidity, clouds, and winds
- Precipitation
- Atmospheric trace gas and aerosol distribution
Cryosphere
- Snow cover
- Ice cover
Volcanoes
Land
- Temperature
- Soil moisture
- Fauna and flore
Oceans
- Temperature
- Currents
- Salinity
- Marine biola

Figure 2 The climate system, consisting of the atmosphere, oceans, land, and cryosphere. Important state variables for each sphere of the climate system are listed in the boxes. For the purposes of this report, the Sun, volcanic emissions, and human-caused emissions of greenhouse gases and changes to the land surface are considered external to the climate system (NRC 2005).

First, climate is never static (Lovejoy and Schertzer 2012). As written in Rial et al. (2004)

> "The Earth's climate system is highly nonlinear: inputs and outputs are not proportional, change is often episodic and abrupt, rather than slow and gradual, and multiple equilibria are the norm."

The assumption of a stable climate system (e.g., the reason for the use of the terminology 'climate stabilization') in the absence of human intervention is a mischaracterization of the behavior of the real climate system. Humans are now adding to the complexity of forcings and feedbacks, but change has always been a part of the climate system. 'Climate change' is, and always has, been occurring. The added word 'change' is, therefore, redundant.

Moreover, there are additional misunderstandings. 'Global warming', which is an increase in the global annual average heat content measured in Joules, is often incorrectly equated to mean 'climate change'. Global warming, however, is just a subset of "climate change."

The term 'climate change', is also being erroneously used to mean only 'anthropogenic caused changes in climate' from nearly 'static' climatic conditions. Frequently, just the human input of greenhouse gases is assumed to be the reason for 'climate change'. For example, NRC (2010) (Climate Stabilization Targets: Emissions, Concentrations, and Impacts Over Decades to Millennia (2010)) states

> "This new report from the National Research Council concludes that emissions of carbon dioxide from the burning of fossil fuels have ushered in a new epoch where human activities will largely determine the evolution of Earth's climate."

Thus, the recommendations to the authors of the volume (not always accepted) were to replace terminology, such as climate change, climate stabilization, and climate disruption, with accurate terminology. When changes in climatic conditions are discussed, it was requested that the actual climate variables (such as temperature, precipitation, length of growing season) that are being altered, be specified. Phrases such as 'changes in regional and global climate statistics' could also be used.

There is a very fundamental reason to limit the use of ‘climate change’ by the impacts community. Key societal and environmental resources, such as water, food, energy, ecosystem function, and human health respond to climate, not just to an incremental change in the climatic conditions. As noted earlier, the assumption of a stable climate system, in the absence of human intervention, is a mischaracterization of the behavior of the real climate system.

However, some authors retained the use of the terminology ‘climate change’. It was acquiesced as long as there was a significant contribution in their chapter to a broad-based assessment of risk to the key resource they were discussing.

Another misused term is ‘global change’, when really what is almost always meant is a local and/or regional change in the environmental conditions, including from climate. The accurate terminology should be ‘environmental change’. The term ‘environmental change’ is, therefore, preferred rather than ‘global change’, as the latter terminology is very much a top-down viewpoint. Almost all impacts on key resources are on the local and regional scale.

We also requested the authors start with the risks and factor in the climate threats after thresholds, etc. were first obtained. This was not done in some chapters, but this information can still be extracted from the text. Obtaining the spectrum of risks first is the more inclusive way to assess threats to key resources, and thus, in the view, to prepare the optimal mitigation and adaptation strategies.

For the climate component of risk, the outcome vulnerability (the top-down) approach relies on skillful weather predictions and analyzes with a regional and a local focus. For weather prediction on time periods of days to a week or two, excellent skillful predictions are available for use in outcome vulnerability assessments. On seasonal timescales, there is also some limited predictive skill to apply to outcome vulnerability assessments, particularly for such well-defined weather events such as an El Niño or La Niña (Castro et al. 2007). However, for decadal and multidecadal predictions little, if any, predictive skill has been shown in hindcast climate model predictions of changes in regional weather statistics beyond what is available to the impacts community via the historical, recent paleorecord and a worst case sequence of weather events.

To illustrate the lack of skill, the conclusions from several papers have been summarized. Fyfe et al. (2011) concluded that

> “….for longer term decadal hindcasts a linear trend correction may be required if the model does not reproduce long-term trends. For this reason, we correct for systematic long-term trend biases.”

Xu and Yang (2012) find that without tuning from real world observations, the model predictions are in significant error. For example, they found that

> …the traditional dynamic downscaling (TDD) [i.e. without tuning) overestimates precipitation by 0.5-1.5 mm d-1…..The 2-year return level of summer daily maximum temperature simulated by the TDD is underestimated by 2-6°C over the central United States-Canada region."

The paper van Oldenborgh et al. (2012) report just limited predictive skill in two regions of the oceans on the decadal time period, but no regional skill elsewhere, when they conclude that:

> "A 4-model 12-member ensemble of 10-yr hindcasts has been analysed for skill in SST, 2m temperature and precipitation. The main source of skill in temperature is the trend, which is primarily forced by greenhouse gases and aerosols. This trend contributes almost everywhere to the skill. Variation in the global mean temperature around the trend does not have any skill beyond the first year. However, regionally there appears to be skill beyond the trend in the two areas of well-known low-frequency variability: SST in parts of the North Atlantic and Pacific Oceans is predicted better than persistence. A comparison with the CMIP3 ensemble shows that the skill in the northern North Atlantic and eastern Pacific is most likely due to the initialisation, whereas the skill in the subtropical North Atlantic and western North Pacific are probably due to the forcing."

Anagnostopoulos et al. (2010) report that

> "…. local projections do not correlate well with observed measurements. Furthermore, we found that the correlation at a large spatial scale, i.e. the contiguous USA, is worse than [even] at the local scale."

Stephens et al. (2010) wrote

> "models produce precipitation approximately twice as often as that observed and make rainfall far too lightly…..The differences in the character of model precipitation are systemic and have a number of important implications for modeling the coupled Earth system …….little skill in precipitation [is] calculated at individual grid points, and thus applications involving downscaling of grid point precipitation to yet even finer-scale resolution has little foundation and relevance to the real Earth system."

van Haren et al. (2012) concluded from their study with respect to climate model predictions of precipitation that

> "An investigation of precipitation trends in two multi-model ensembles including both global and regional climate models shows that these models fail to reproduce the observed trends….. A quantitative understanding of the causes of these trends is needed so that climate model based projections of future climate can be corrected for these precipitation trend biases…. To conclude, modeled atmospheric circulation and SST trends over the past century are significantly different from the observed ones."

Sun et al. (2012) found that

> "…in global climate models, [t]he radiation sampling error due to infrequent radiation calculations is investigated …….. It is found that…. errors are very large, exceeding 800 W m^{-2} at many non-radiation time steps due to ignoring the effects of clouds…."

There is an important summary of the limitations in multidecadal regional climate predictions in Kundzewicz and Stakhiv (2010) who succinctly conclude that

> "Simply put, the current suite of climate models were not developed to provide the level of accuracy required for adaptation-type analysis."

Since the top-down outcome vulnerability approach depends on skillful decadal and longer regional and local climate predictions, yet they have shown little if any skill, another approach is needed.

For this reason, the volume set of five books presents an alternate approach – the bottom-up, resource-based outcome (contextual) vulnerability perspective. The goal of the set was to focus on the climate component of stress but also consider, in-depth, other environmental and social threats.

The text of the articles is written at a level that allows undergraduate students to understand the material, while providing active researchers with a ready reference resource for information in the respective field.

The questions requested to the authors address with respect to a specific resource were:

1. Why is this resource important? How is it used? To what stakeholders is it valuable?
2. What are the key environmental and social variables that influence this resource?
3. What is the sensitivity of this resource to changes in each of these key variables? This includes, but is not limited to, the sensitivity of the resource to climate variations and change on short (e.g., days), medium (e.g., seasons), and long (e.g., multidecadal) timescales.
4. What changes (thresholds) in these key variables would have to occur to result in a negative (or positive) response to this resource?
5. What are the best estimates of the probabilities for these changes to occur? What tools are available to quantify the effect of these changes? Can these estimates be skillfully predicted?
6. What actions (adaptation/mitigation) can be undertaken in order to minimize or eliminate the negative consequences of these changes (or to optimize a positive response)?
7. What are specific recommendations for policymakers and other stakeholders?

There are also overview chapters that discuss the science of the resource.

Several authors insisted on focusing on the use of the outcome vulnerability (top-down) approach based on the multidecadal GCM projections (statistically or dynamically downscaled) as the starting point of their chapters. The chapters were accepted, despite this shortcoming, because when they finally discussed adaptation in their text, they did present the broader-based bottom-up focus that is the centerpiece of the volume. Readers,

however, need to be aware that the top-down, GCM scenarios are only a subset, at best, of what is plausible in the coming decades. Multidecadal predictions of changes in regional and local climate statistics have not shown skill when run in a hindcast mode for the past several decades.

In summary, the goal of the five-volume set of books is to document the value of a bottom-up, resource-based assessment of risk to key resources, as illustrated schematically in Figure 3a–e. Most, but not all, authors accepted this framework. This can be assessed without having any predictability on

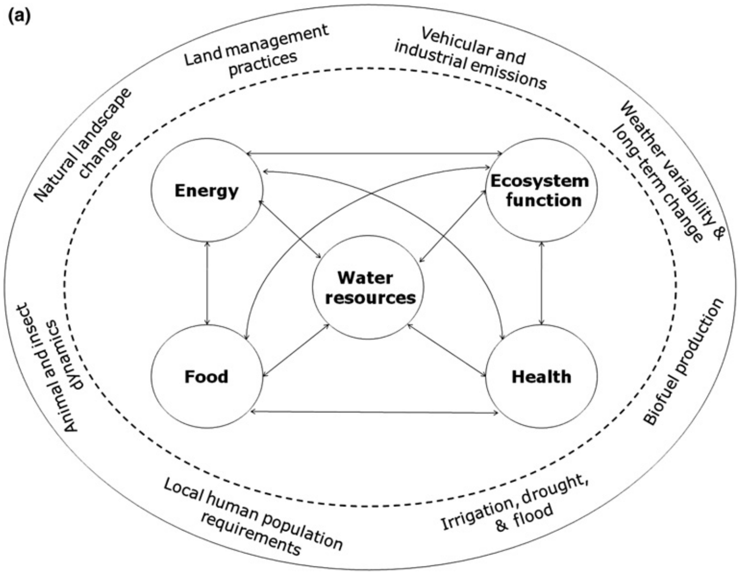
(a)
Land management practices
Vehicular and industrial emissions
Natural landscape change
Weather variability & long-term change
Energy
Ecosystem function
Water resources
Food
Health
Animal and insect dynamics
Biofuel production
Local human population requirements
Irrigation, drought, & flood

Figure 3a Contextual vulnerability for water resources (Hossain: Editor)

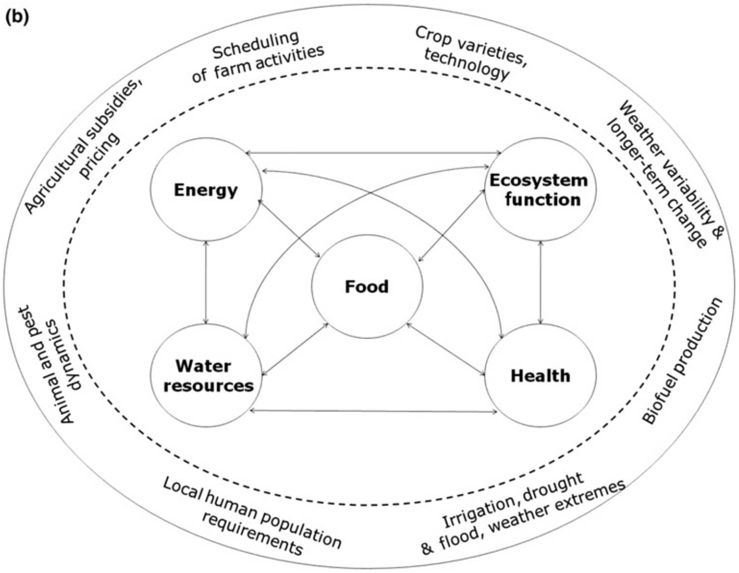
(b)
Scheduling of farm activities
Crop varieties, technology
Agricultural subsidies, pricing
Weather variability & longer-term change
Energy
Ecosystem function
Food
Water resources
Health
Animal and pest dynamics
Biofuel production
Local human population requirements
Irrigation, drought & flood, weather extremes

Figure 3b Contextual vulnerability for food (Niyogi: Editor).

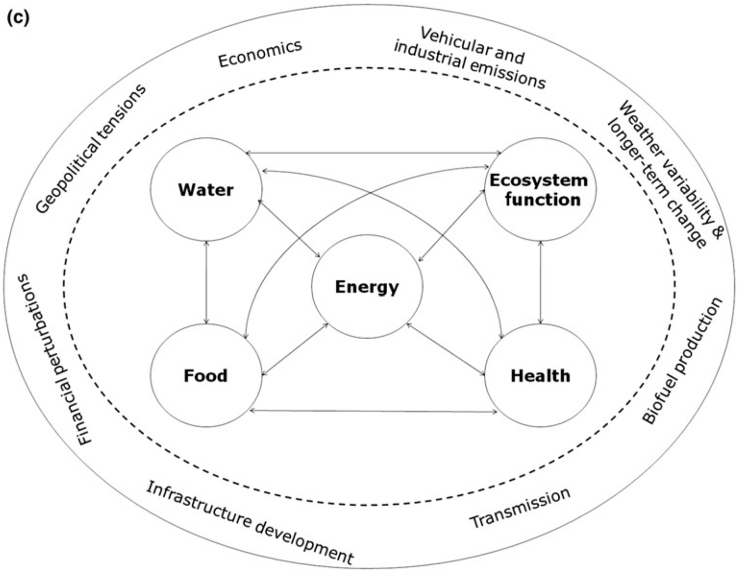
(c)
Economics
Vehicular and industrial emissions
Geopolitical tensions
Weather variability & longer-term change
Water
Ecosystem function
Energy
Food
Health
Financial perturbations
Biofuel production
Infrastructure development
Transmission

Figure 3c Contextual vulnerability for energy (Kallos: Editor).

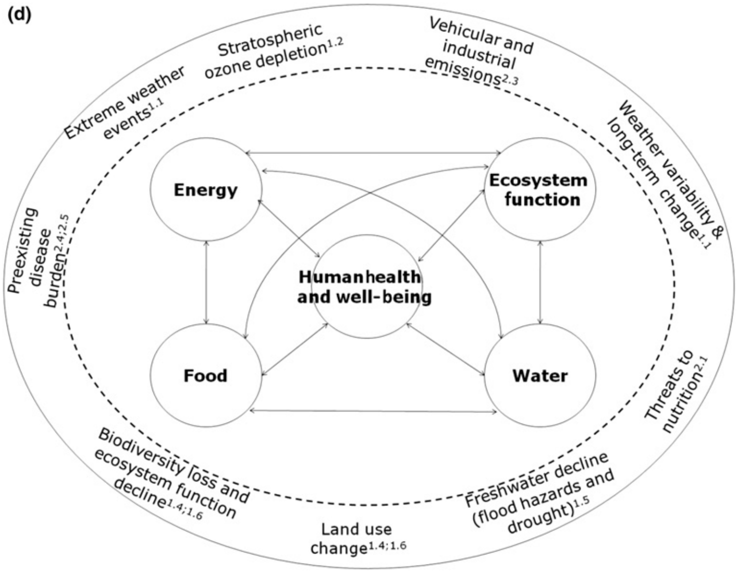
(d)
Stratospheric ozone depletion$^{1.2}$
Vehicular and industrial emissions$^{2.3}$
Extreme weather events$^{1.1}$
Weather variability & long-term change$^{1.1}$
Energy
Ecosystem function
Preexisting disease burden$^{2.4;2.5}$
Humanhealth and well-being
Food
Water
Threats to nutrition$^{2.1}$
Biodiversity loss and ecosystem function decline$^{1.4;1.6}$
Land use change$^{1.4;1.6}$
Freshwater decline (flood hazards and drought)$^{1.5}$

Figure 3d Contextual vulnerability for human health and well-being (Adegoke and Wright Editors).

multidecadal time periods. It is an alternative (and more inclusive) perspective than the IPCC top-down outcome vulnerability approach which starts with the GCMs as the overarching framework. In the bottom-up approach, the scenarios from the GCM predictions should only enter after the specific threats to the resources are determined and even then, they provide, at best, a limited set of insights into what is possible.

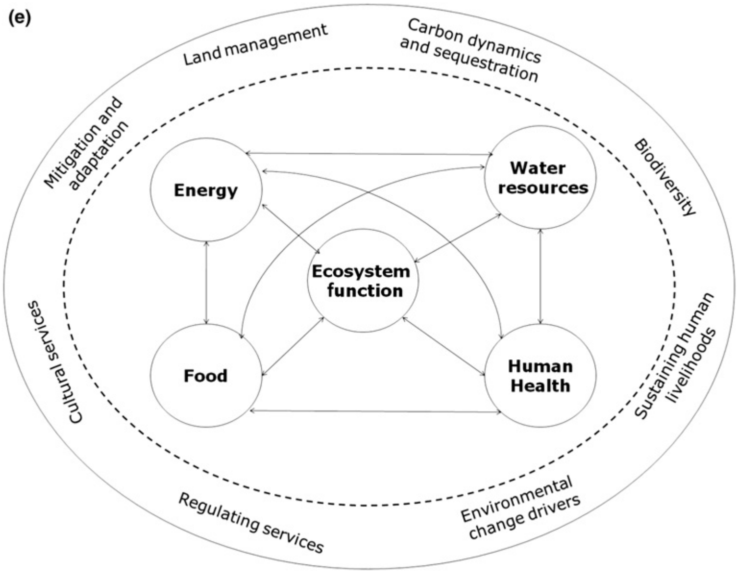
(e)
Land management
Carbon dynamics and sequestration
Biodiversity
Sustaining human livelihoods
Environmental change drivers
Regulating services
Cultural services
Mitigation and adaptation
Energy
Water resources
Ecosystem function
Food
Human Health

Figure 3e Contextual vulnerability for ecosystem function (Seastedt and Suding; Editors).

We look forward to feedback from the readers.

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Jimmy Adegoke,
Faisal Hossain,
George Kallos,
Dev Niyogi,
Timothy Seastedt,
Katharine Suding,
Caradee Y. Wright and
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Preface - Vulnerability of Water Resources to Climate

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No matter how differently we all prefer to classify the key resources for the human civilization and the health of our planet, water will always remain a common denominator. In fact, one could argue that water is most intimately linked as a resource with other key resources such as human health (imagine cholera, malaria, or sanitation), food (imagine the green revolution to feed a hungry population), energy (about 10% of the world's energy is generated from hydropower), and ecosystem function (where water availability dictates the type of flora and fauna). Perhaps no other resource is as important to so many other resources or is as starkly dependent on so many other resources.

Like the other volumes of the climate encyclopedia, the volume on water was compiled with the mindset that understanding the vulnerabilities facing our water resources today requires a very bottom–up or contextual approach that is missing in today's literature. After all, it is this contextual approach that a stakeholder can use for adaptation or decision making at the local scale. Thus, this volume, like the encyclopedia overall, makes a very conscious attempt to move away from the plethora of top–down and outcome-oriented vulnerability assessment studies available at present. Instead, the volume presents an alternative but more actionable view of water as a resource. It asks the following questions:

- What are the key issues or threats facing the availability of water resources today?
- How do we use the understanding of these issues to make the health of our planet and human civilization more resilient in the near future?

Since the 'near future' is a key focus, this volume wholeheartedly avoids assessments based purely on the commonly studied 50- or 100-year emission-driven scenarios of future climate. The more pressing question for local stakeholders is:

- "What do we need to do right now so that we can do an even better job in the future in maintaining a resilient civilization in our region?"

This volume is designed for both the busy reader needing specific information for an action-oriented agenda and the more diligent student wishing to build a comprehensive theoretical background on water resources vulnerability. The volume is divided into two sections. The first section presents a series of 10 chapters that covers the 'state-of-the-art' theory on our physical understanding of water resources variability. The second section presents 15 region-specific case studies on the characterization of water resources vulnerability and the lessons that we have learned so far, which of course, is very contextual. Thus, the more conscientious reader should read the entire volume systematically, beginning with the very convincing overview of the concept of contextual vulnerability assessment by Bloeschl et al. This is followed by a synopsis of the best estimate of the quantity of water we have in this world today by Balazs Fekete. Precipitation often mirrors the available water as a resource. The human civilization has had to devise numerous infrastructures (dams, channels, urban drainage, irrigation schemes, reservoirs, etc.) to deal with the extremes of water availability, which are difficult to adapt to. The third chapter by Groisman et al. therefore provides a synopsis on what the observations tell us now about precipitation extremes around the world. The two chapters in this section deal specifically with mountains, which often function as a 'funnel' to trap atmospheric moisture in a form that is more usable as a resource. Ana Barros presents an overview of our current understanding of the physics of this moisture entrapment and precipitation in mountainous regions (Chapter 5.4). Deepak Ray presents the state of the art on very sensitive ecosystems that are located high up in the mountains of the tropics (called tropical montane cloud forests) in select regions of the world (Chapter 5.5). Authors Marshall Shepherd and Burian et al. present a detailed rendition of the impact of urban infrastructure on climate (particularly precipitation) and the implications on sustainability of city centers, respectively. Analysis of paleoclimate data is considered essential in any contextual vulnerability assessment and for verifying the attribution of potential human contribution to the current or future state of water availability. Rashid et al. provide a very timely chapter entirely on the use of paleoclimate data to understand abrupt climate change. Finally, the last two chapters of the first section provide a view of what is to come in the future for measurement, monitoring, and vulnerability assessment. Space-borne sensors are becoming increasingly cost effective and accurate in detecting the changes in water fluxes in difficult-to-access regions. Two particular types of satellites are considered in this volume – passive sensors that can estimate precipitation (Chapter 5.9) and geodetic sensors that can measure changes in gravimetry (Chapter 5.10) that are often dictated by changes in terrestrial water storage.

The next section (Section 2) provides a series of 15 case studies by region, such as the Arctic, North America, Andes, China, East and West Africa, Sahara, South Asia, and Europe. These chapters may be read as stand-alone contributions by the busy reader if desired. However, the chapters are organized per region or theme so that continuity is not lost when moving from one chapter to the next. Several of the chapters have themes that cut across to another volume. For example, the chapter by Akanda et al. on the role of hydrology on cholera in the Bengal Delta (Chapter 5.22) will be found to be highly relevant to the volume on Human Health. Similarly, the chapter by Wood et al. on the sustainability of hydropower (Chapter 5.12) relates closely to the volume on Energy.

Other than the invaluable services of the editor-in-chief (Roger Pielke Sr.) and the 'always-available' Elsevier support staff, this volume would not have been possible without the selfless peer service of the many reviewers who helped ensure quality of each published chapter. In particular, we would like to acknowledge the following people who spent countless hours going methodically through the chapters to improve its

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content: Michael Durand, Hatim Sharif, Jonathan Gourley, Marloes Bakker, Eric Rosenberg, Matthew Cohen, Holger Hoff, Alfred Kalyanapu, Steve Burian, Qingyun Duan, Mervin Peart, Petra Dam, Hyongki Lee, James Voogt, Nathalie Voisin, Tamlin Pavelsky, Shuhab Khan, John Fazio, and many others who have wished to remain anonymous.

We are poised delicately in the twenty-first century where water as a resource will play an increasingly more critical role for human civilization and the health of our planet. To make the best use of this precious resource and understand its impact or implication of use, we need knowledge *now* at a scale practically relevant for decision making and adaptation. This volume aims to achieve just that through a collection of 25 chapters by leading authorities. It is our hope that this volume can provide the most actionable knowledge on water resources for the vast community of busy stakeholders, policy planners, and the engaged student looking for education appropriate for the twenty-first century.

5.01 Emerging Approaches to Hydrological Risk Management in a Changing World

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5.01.1 Unexpected Events and Risk Management

7 August 1994. The township of Tirlyan in the Republic of Bashkortostan, Russia. The dam operators are at the verge of panicking. There had been major rainfalls on the previous days and the water level of the Tirlyan reservoir had been increasing steadily during the day. While the dam was relatively small with 10 m height, the volume was 8.6 million cubic meters and posed considerable danger for the downstream villages of Tirlyan, Avzalovo, Kazylyarovo, and Alakagovo. One of the segment gates had been blocked years before because of concerns about sabotage, and the operators were hectically attempting to release the gate. No way that the remaining gates would be able to cope with the floodwaters. 16:20. The gate is still blocked and the water levels have reached the top of the dam – an earth fill dam constructed in 1917. Villagers have flocked to the banks of the Belaja river downstream of the dam to watch the spectacle. Minutes later, the water of the reservoir starts to overtop the dam. A breach forms and a wide section of the dam gives way. The flood wave spills over the downstream plain and gets hold of dozens of bystanders. The spectacle had turned into a disaster. Many people can be saved, but the flood takes its death toll among the villagers (Moscow News, 19 August 1994).

Avoiding events like this is one of the main purposes of hydrological risk management. In hindsight, the cause of the failure was almost trivial. With a little more lead time, it would have been easy to open the gate and avoid the disaster. Also, it was not a design problem. It was a contingency none of the dam operators had foreseen.

Society is becoming increasingly aware of the risks associated with hydrologic extremes, in particular floods and droughts. With climate being high on the political agenda, it is clear that the links between climate and hydrological risks have become a major concern for politicians, flood managers, and citizens alike. There is a debate on whether there have been climate-related increases in the severity and frequency of floods and droughts in the past decades. While numerous devastating floods and droughts have occurred recently, it has been argued that confirmation bias could play a role in the attribution to causes, that is, the tendency to favor information that confirms existing preconceptions (Taleb 2007; Merz et al. 2012). Increases in damage may be more related to socioeconomic change than to hydrologic change (Di Baldassarre et al. 2010; Bouwer 2011). In a particular catchment, extremes may or may not have increased but the fact remains that there is an urgent need for managing hydrological risks in the best possible way. Many countries have passed new legislation such as the EU Flood directive (EU 2007) that explicitly requires the establishment of flood risk management plans. There are similar drought risk management plans in a number of countries and states (e.g., Jacobs et al. 2005). The concept of integrated hydrological risk management (IHRM) (for both floods and droughts) is currently implemented widely.

Fundamental to the concept of risk are the notions of hazard and vulnerability, which both contribute to the risk. Hazard relates to a dangerous phenomenon (flood or drought), human activity (river damming), or condition (water scarcity) that may cause societal disruption or environmental damage (see the Hyogo Framework for Action, UN-ISDR 2005), whereas vulnerability relates to the characteristics of the people, the property, or the environment that are at risk. If one is to manage risks one can try to manipulate the hazard, the vulnerability, or both. Figure 1 shows the 2005 flood in Tirol, Austria. Clearly, the risk is high because of the presence of the houses. This is a vulnerability problem.

Given the recent and expected future changes in the water-related environment, developing strategies of hydrological risk management and implementing them pose a number of challenges. In this chapter, we will discuss the methods that can be used in IHRM and review emerging approaches of how to prioritize the implementation of these methods.

5.01.2 Elements of Integrated Hydrological Risk Management

The hallmark of IHRM is that a variety of actions are considered and implemented in an integrated way. This sets IHRM

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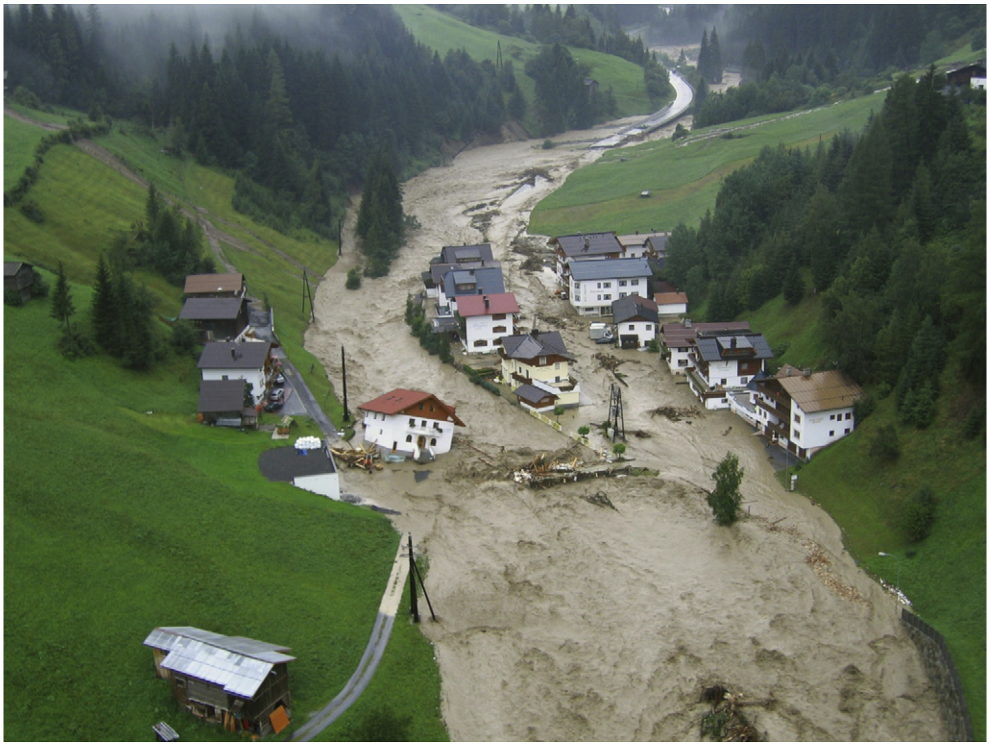

Figure 1 August 2005 flood in Tirol Austria. Only a few decades ago, when there was not a single building at this location of the valley, a similar flood would not have been considered a disaster.

apart from traditional flood protection (and drought abatement) where individual measures were considered in isolation and sometimes the focus was on structural measures (such as dams) alone. Conceptually, the possible measures (or actions) are usually arranged along a hypothetical time axis of the disaster risk cycle that consists of four phases: mitigation, preparedness, response, and recovery (e.g., Thieken et al. 2007). In the case of flood risk management, mitigation involves a range of structural measures to reduce hazard and/or vulnerability, such as dams, levees for flood protection, polders of flood mitigations, and nonstructural measures such as land use zoning and insurances. Preparedness involves the establishment of emergency plans, the training of flood management staff, awareness building of the general public, and issuing flood warnings. Response involves immediate actions for protecting life and property such as evacuations and the provision of food and shelter. Recovery involves longer-term responses such as cleanup and rebuilding of structures. Preparedness, response, and recovery aim to reduce vulnerability. Nonstructural measures can be highly efficient. For example, the 2002 flood in the Czech Republic led to a much smaller number of flood-related fatalities than the 1997 flood, although it was larger. This was a result of the increased flood awareness and preparedness (Di Baldassarre et al. 2010). A similar cycle with a diversified mix of measures applies to drought risk management (UNDP 2011) but the time scales tend to be longer because of the more long-term nature of droughts.

The relative efficiency and effectiveness of individual measures depend on the local conditions (Samuels et al. 2010; Borga et al. 2011). Because of this, prioritizing the measures is difficult, particularly given the recent changes in demography, economy, assets, land use, and climate as they all contribute to the risk (Hooijer et al. 2004; Thomalla et al. 2006; Birkmann and von Teichman 2010; Etkin et al. 2011; Solecki et al. 2011). There are two approaches of addressing the prioritization of risk management measures (Figure 2).

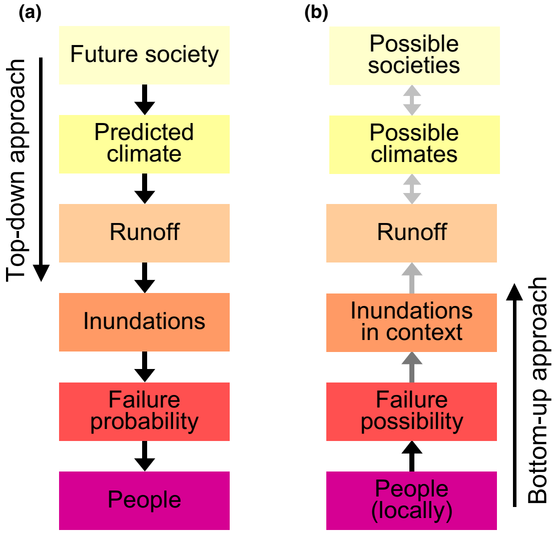

Figure 2 (a) Traditional top-down approach to hydrological risk assessment based on climate projections. (b) Bottom-up approach to hydrological risk assessment that is vulnerability or resilience centered. Approaches are illustrated by a fluvial flood risk example. Gray arrows indicate less dependence than black arrows.

The first, termed the top-down approach, starts from the climate forcing, cascading down information to the people affected by the floods or droughts. The second, termed bottom-up approach, starts from the people affected and explores possibilities of risk management (Dessai et al. 2009a,b; Wilby and Dessai 2010). These two approaches are discussed in the two next sections.

5.01.3 Top-Down (Economic) Approach to Risk Assessment Based on Probabilities

The 'top-down' approach is designed to represent the main processes causing the hazard and its consequences. In the case of climate impacts on floods (Figure 2), the 'top-down' approach starts at the global scale and cascades information from emission scenarios of future societies to simulated climates using global and regional climate models, to runoff using hydrological models, to inundations using hydrodynamic models, and to damage costs using economic models. The top-down approach is motivated by an economic paradigm. Hence, risk is defined from an economic perspective, specifying hazard as the occurrence probability of a flood (or drought) event, vulnerability as the damage cost in monetary terms, and (economic) risk as the product of the two. This leads to an optimization problem that aims at identifying the most economic management strategy among those discussed in the previous section.

The 'top-down' approach is the most widely used approach for impact and adaptation assessments (Blöschl et al. 2007). The 'top-down' approach is sometimes termed the 'predict-then-act' method as projected scenarios are the starting point and the main emphasis (Dessai and Hulme 2004). Scenarios differ in terms of the global development (affecting greenhouse gas emissions and simulated climate) and in terms of local development such as agricultural development, urbanization, construction of infrastructure, and other human activities (Kundzewicz et al. 2002; Wilby et al. 2009). The entire cascade is rigorously model based. Often, the scenario analysis is complemented by narrative descriptions of multiple facets of possible futures to ensure internal consistency (Merz et al. 2010). Applications of the top-down approach to hydrological risk assessment abound (e.g., Johnson and Weaver 2009; Lugeri et al. 2010; Veijalainen et al. 2010), many of which have an explicit focus on economics (e.g., Aerts and Botzen 2011; Zhou et al. 2012).

The appeal of the top-down approach is that it is conceptually straightforward and elegant as it mimics what is considered the main process cascade. Two questions arise: (1) should minimizing costs be the main societal goal and (2) is it possible to quantify future hazards and vulnerabilities to the accuracy needed?

1. Societal goals must, of course, be set in a political discourse. Surprisingly, there is relatively little open debate on this in hydrological risk management. Although the economic paradigm seems to be the most frequently adopted today, in practice, risk management measures often depart from it, even if the IHRM in a particular catchment is set in an (economic) risk framework. This is illustrated by examples from fluvial flood management: Emergency actions such as evacuations are rarely based on cost/benefit considerations but on (social) humanitarian goals. Also, when prioritizing flood defense structures, often, worst-case scenarios that are at variance with the economic optimality goal are considered. Since extreme floods are usually economically less important than smaller floods if a long period is considered (Merz et al. 2009), risk aversion functions can be used to give greater weight to extreme events (Merz et al. 2010), which again deviates from the economic optimality goal toward a more social perspective. Similarly, in issuing flood warnings, maintaining credibility is often of higher priority to the flood warning staff than economic optimality (Blöschl 2008). A more explicit debate on the goals of IHRM in a changing world would be desirable.
2. The accuracy of quantifying future hazards and vulnerabilities has received more attention. Each modeling step of the top-down approach (Figure 2) introduces uncertainties that may lead to different prioritizations of risk management measures, depending on the assumptions made, and in fact to ineffective risk management (van Pelt and Swart 2011). The concept of economic risk hinges on the interpretation of the hazard as a probability. However, it may not be possible to specify such probabilities because of the nature of the socioeconomic processes (Grübler and Nakicenovic 2001). There are therefore two schools of thought in the top-down approach (Dessai and Hulme 2004). The first rigorously defines probabilities of, say, future droughts for estimating the risk. The second interprets scenarios as possible future developments, so the probabilities are more vaguely defined. Another dilemma is that, per definition, one is interested in conditions that are different from the past (in some ways), so testing the models of the cascade to past data does not fully confirm their credibility. Many Earth scientists hold a positivistic world view that assumes that, if enough data are analyzed in the right way, one can understand and resolve even the most complex problems, so the line of thought is that more detailed models will solve the dilemma. Hydrology has a long history of scientific discourse about the primacy of the reductionist (process-based or Newtonian) world view or the alternative holistic (data-based or Darwinian) world view (e.g., Sivapalan 2003; Savenije 2009; Merz et al. 2011). Figure 3 illustrates the point. Assume that we were in the year 1900 and had today's complex process models and computing power. Even with these it would be essentially impossible to predict the evolution of floods in the twentieth century for the Danube. The broader discussion in hydrology suggests that in many instances reductionist approaches are needed for identifying causal links, but there are many cases of societal relevance where feedbacks and emerging patterns make the reductionist approach questionable, so more holistic approaches should be preferred (Peel and Blöschl 2011; Blöschl and Montanari 2010). Similar arguments have been forwarded in Earth System modeling, in particular at the interface between socioeconomic and biophysical processes (Pielke 2004; Koutsoyiannis et al. 2009; Wilby and Dessai 2010; Sivapalan et al. 2012).

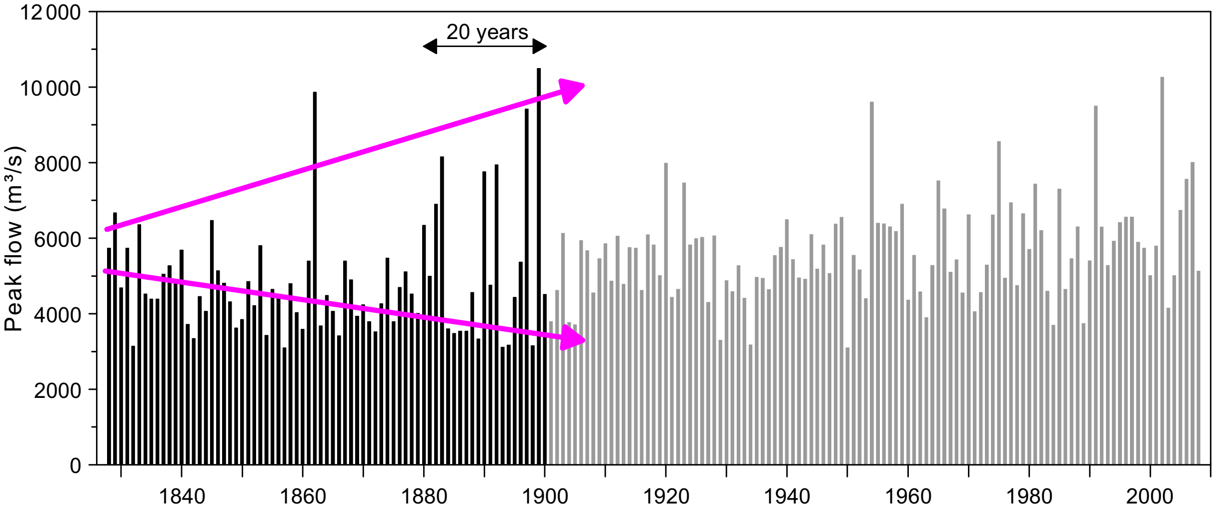

Figure 3 Maximum annual floods of the Danube at Vienna. Based on the data 1828–1900 (highlighted in black) it would be essentially impossible to predict the evolution of floods in the twentieth century for the Danube even if today's complex process models and computing power were available. Pink arrows indicate possible evolutions of large and small floods. Modified from Blöschl and Montanari (2010).

One way of addressing the uncertainty dilemma is to perform probabilistic uncertainty analyses (Dessai and Hulme 2004). Emerging methods represent the uncertainty of the hazards and/or vulnerabilites by Ensemble (Monte Carlo) methods while keeping a process-based approach that allows one to profit from available process knowledge. A number of recent studies have demonstrated the feasibility of this approach for the case of inundations due to fluvial floods (e.g., Apel et al. 2004; Di Baldassarre et al. 2009; Merz et al. 2010). By recognizing randomness and uncertainty, such a framework does not yield deterministic predictions, but the uncertainty estimates can be very useful. Extending these probabilistic uncertainty frameworks to a range of processes relevant to hydrological risk management has, *inter alia*, been proposed by Koutsoyiannis et al. (2009) and Blöschl and Montanari (2010), and Wetterhall et al. (2011) presents a study of probabilistic uncertainty analyses of hydrological risk in Sweden.

5.01.4 Bottom-Up (Social) Approach to Risk Assessment Based on Possibilities

The 'bottom–up' approach (Figure 2) starts at the local scale of individuals, households, and communities and explores the factors and conditions that enable successful coping with hydrological extremes (Wilby and Dessai 2010). The bottom-up approach is motivated by a social paradigm. Hence, risk is not defined in monetary but in more qualitative terms. The main goal is not to find the most economic management strategy but to ensure the well-being of people by reducing vulnerability and enhancing resilience (the ability to recover after an event). It does not take climate projections as a starting point but the vulnerability and resilience of the risk-related system itself (van Pelt and Swart 2011). It is sometimes termed the 'assess-risk-of-policy' method as it explores alternative policies first.

Although the top-down approach is currently more popular, realization of the importance of the bottom-up approach is emerging: *"Society will even benefit much more from a greater understanding of the vulnerability of climate-influenced decisions to large irreducible uncertainties than it will from extremely expensive attempts to increase the accuracy and precision of climate predictions. An alternative approach to the conventional one based on climate prediction would therefore focus on exploring how well strategies perform across wide ranges of assumptions and uncertainties (Robust Adaptation Decision-Making)."* (European Commission 2009, p. 13).

The bottom-up approach differs from the top-down in that the main aim is to reduce vulnerability and enhance resilience. It has therefore particular value in countries in which the vulnerabilities to floods and droughts tend to be high such as in the developing world (Di Baldassarre et al. 2010; UNDP 2011). Also, it may be more ethically justified as it puts people center stage. Typically, the strategies are not optimal from an economical perspective but they are robust, that is, they are designed to perform well over a wide range of assumptions about the future and potentially extremely negative effects. In other words, they are 'low-regret' strategies. Note that 'no-regret' strategies do not exist in any kind of nontrivial decision making. Since the starting point is local communities, they tend to be more creative and inclusive of a broader range of information, such as governance and lessons learned from the past and other catchments, context-dependent information, contingencies, and narratives (Pielke 2004). Clearly, the Tirlyan disaster could not have been anticipated by a top-down risk approach. It may have been possible to speculate in advance about the possibilities of blocking the gate based on *local* experience, but this is not a type of information that can enter into a formal optimization analysis. The bottom-up approach is therefore based on 'possibilities' rather than on probabilities. Because of this, it tends to be less dependence on probabilities inferred from the predictive scenario approach (Sarewitz et al. 2003). The preference for alternative strategies may become

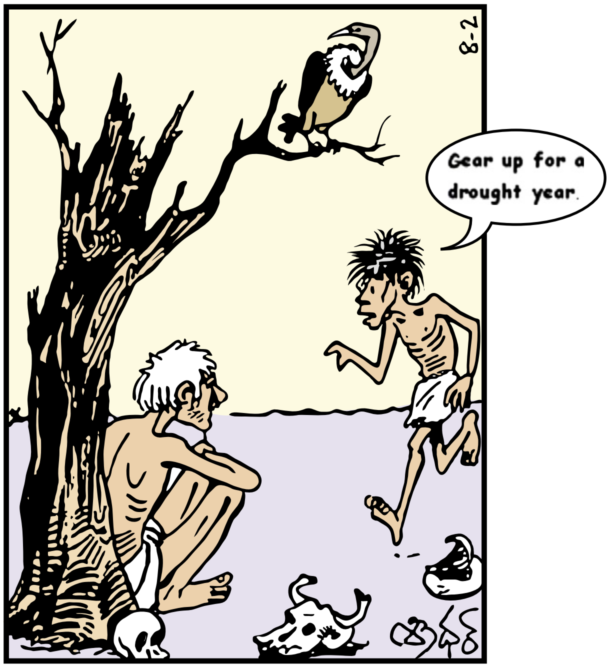
8-2
Gear up for a drought year.

Figure 4 Drought predictions, however accurate, delivered by the young man are completely useless to the old man because of his high vulnerability. The course of action is clear; the actions just need to be done. [Available online at http://sriks6711.wordpress.com/2009/08/03/india-is-drought-hit-in-2009.]

insensitive to the assumptions of climate scenarios since other factors (including local socioeconomic factors) dominate, but this will depend on the local setting. This is a notion that Prudhomme et al. (2010) term 'scenario-neutral'. In Figure 2, the weaker sensitivity (or lack of sensitivity) to the scenario predictions is indicated by the gray arrows. Local information on the social characteristics related to floods and droughts may indeed be more relevant than global predictions. Consider the cartoon in Figure 4. It appears that the drought predictions, however accurate, delivered by the young man are completely useless to the old man sitting by the tree because of his high vulnerability and the lack of options he has. The point of the bottom-up approach is that scenario predictions are not helpful for deciding how to improve the fate of the people in the cartoon. The course of action needed is clear; the actions just need to be done.

However, the pros of the bottom-up approach come at an expense. It is significantly more 'messy' and lacks the conceptual elegance of the top-down approach. The most relevant consequence is a more difficult interaction with stakeholders. As a matter of fact, the effort to explore what the future will be looks more appealing than a seemingly unstructured analysis of the present. Indeed, vulnerability is determined by a host of factors including variations in wealth, social equality, food availability, health and education status, physical and institutional infrastructure, access to natural resources, and technology (Wilby and Dessai 2010) that condition the analysis and prevent to set up a unified framework for the bottom-up approach. Also, the methods tend to be more messy, as is often the case in the social sciences (see, e.g., the evaluation of participative methods in water resources, Carr et al. 2012). Methods often involve exploratory modeling approaches in which multiple runs of simulation models are used to systematically explore the implications of a wide range of assumptions and contingencies (Dessai et al. 2009a). These assist in making policy arguments. An important role is played by historical data in the case study or similar catchments. Equally important, a range of methods from the social sciences are used, such as surveys, impact diagrams, mind maps, causal loop methods, and visualization methods involving the local risk managers and stakeholders (e.g., UNDP 2011; Waser et al. 2010), to explore the perceived or real causal structure of the system.

Since the problem is messy, case studies play an important role. The vulnerability approach of Simonovic (2010), for example, starts from analyzing existing policies and management practices in a Canadian catchment with respect to critical flood and drought situations, which he then transforms into corresponding critical meteorological conditions. Schelfaut et al. (2011) focus on enhancing the resilience by identifying the opportunities and bottlenecks of flood risk management in a number of European catchments, such as institutional interplay, flood management tools, and risk communication. For a flood risk case study of the river Rhine van Pelt and Swart (2011) conclude "*The 'assess-risk-of-policy' approach recognizes local interests and conditions, and offers possibilities to deal with uncertainties that cannot be quantified, by focusing on the resilience of the system. First results of this method show that it can offer policy makers a new, complementary tool for evaluating adaptation strategies that also addresses their non-climate priorities and maybe [provides] a different view on the urgency of adaptation to climate change.*" In Southern Austria, experience with the 2003 drought was used to assess the vulnerability of the water supply system and to enhance the connectivity of the infrastructure (Blöschl et al. 2011). Harou et al. (2010) explore the economic effects and potential adaptation strategies of water trading of California's water supply system using past droughts from paleorecords rather than climate projections. Similarly, Watts et al. (2012) test the resilience of drought plans in England to droughts that are outside recent experience using nineteenth century drought records. The method combines system modeling with an interactive approach that asks water system managers to work through the actions that they would take at different stages of the drought, without knowledge of subsequent drought development.

In the top-down approach, the hydrological modeling is usually performed in a mechanistic way by running hydrological models with prescribed boundary conditions (e.g., climate or land use scenarios), whereas the bottom-up approach has a more creative role for hydrologists to play. Their role is explorative modeling across a wide range of assumptions, contingencies, and uncertainties taking into account the expertise of local risk managers and stakeholders. The aim is to assist them in understanding the potential consequences of alternative policy options.

5.01.5 Accounting for Black Swan Events

The previous two sections discussed two alternative approaches to prioritizing hydrological risk management. There is another

Figure 5 A black swan among numerous white swans is unexpected but may be the important one. There is a potential for Black Swan events in hydrology that are unexpected but have high impact from a societal point of view. [Available online at http://www.lonelyplanet.com/japan/hokkaido/images/black-swan-among-white-swans-hokkaido$24256-1.]

facet to it. Taleb (2007) observes that the worst disasters in history have been the unexpected ones because of the inability to brace against them. He terms such unexpected large-impact events 'Black Swan events,' based on the anecdote that, before the discovery of Australia, all swans were considered to be white because of the lack of black swan sightings in the Western world (**Figure 5**). For such Black Swan events, prior risk calculations are, invariably, grossly in error. An example is the 2001 terrorist attack on the World Trade Center (Sarewitz et al. 2003). Black Swan events are unexpected and have large impacts and, interestingly, failed predictions can always be explained *in retrospective*.

Experience with unexpected events with large consequences abounds in hydrological risk management – that is to say after the fact. The Tirlyan disaster is a case in question, and there are many more. They make up the 'lessons learned' from any recent disaster. For example, the lessons learned from the 2002 flood in Austria include the following situations to be considered: blockage of reservoir spillways by an excessive amount of woody debris due to landslides into the reservoir, leaky oil tanks in the cellars of houses due to buoyancy when being flooded, and the resulting oil spills, missing local details in flood management plans such as passageways under railway embankments causing major unexpected flooding beyond the embankment. All these events were unexpected, were created by context and contingencies, and had large (potential) consequences, but they could have been easily avoided if only one had known of them *a priori*.

Unexpected large events are produced by the nonlinearities of the system (Blöschl and Zehe 2005; Koutsoyiannis et al. 2009), in particular in the interplay of the biophysical and the social system (Sarewitz et al. 2003; Sivapalan et al. 2012). Climate variability has therefore the potential to produce Black Swan events for hydrology that are unexpected but have high impact from a societal point of view.

The implications for hydrological risk management are important. The bottom-up approach has more potential to prepare for unexpected events than the top-down approach as the focus is on reducing the vulnerability of the system by robust methods. As Taleb (2007) noted *"it is much easier to deal with the Black Swan problem if we focus on robustness to errors rather than improving predictions"* (Taleb 2007, p. xxiv). For a flood management system, for example, the vulnerability of the system can be reduced by using free overflow spillways rather than funnel-like morning glory spillways since the former are more robust against hydraulic overload, by designing spillways for dikes (which is not usually done), and by planning for redundancy in emergency plans. For a drought management system, the vulnerability of the system can be reduced by increasing the connectivity of water supply infrastructure and converting permanent abstraction licenses to time-limited status, among other low-regret strategies (Wilby and Dessai 2010). They may not be optimum in an economic sense but may be more robust than alternative approaches to extreme events with large consequences. The bottom-up approach starting with the policy options at the local scale may also be more creative by exploring a wide range of possibilities causing flood- and drought-related disasters. The actual measures taken may be quite different from those resulting from the top-down approach, as in the bottom-up approach one may rank the measures by the harm they may cause rather than by their contributions to total economic risk.

The flood risk management study of Wardekker et al. (2010) is interesting in that it explores imaginable surprises, something they term 'wildcards.' The study proposes an uncertainty-robust adaptation strategy of strengthening the resilience of the city of Rotterdam, using literature study, interviews, and a workshop. The 'wildcards' or imaginable surprises for the area include thermohaline circulation collapse, port freezing events, port malaria incidents, modified German water safety policy, enduring heat and drought, extreme storm, and failure of the storm surge barrier during an extreme storm. Their resilience approach is designed to make the system less prone to disturbances, enable quick and flexible responses, and make it better capable of dealing with surprises than traditional predictive approaches.

5.01.6 Conclusions

The two main approaches to hydrological risk management are the top-down approach that starts from the projected scenarios and the bottom-up approach that starts from the vulnerability of the communities in question. While the top-down approach is conceptually appealing as it mimics the main process cascade and strives for economic optimality, the probabilities used in this approach may be difficult to estimate, in particular in a changing world. The bottom-up approach is ‘messier’ involving methods that can be less clearly structured, but it has a social motivation and is more amenable to accounting for surprises as it strives for reduced vulnerability and increased resilience by robust methods. In the bottom-up approach, risk involves possibilities rather than probabilities. The bottom-up approach has an important and creative role for hydrologists to engage in explorative modeling to assist local risk managers and stakeholders in defining policy options.

Van Pelt and Swart (2011) noted that too much focus on climate scenarios alone may lead to ineffective risk management. Montanari et al. (2010) conclude “*Offering insightful explanations for predicted changes may be more helpful than perfecting the estimates of what are inherently uncertain changes. Such a nuanced assessment will gain wider acceptance in society and will bring more credibility to the research community*.” We argue in this paper that the possibilistic thinking of the bottom-up approach (including worst cases) should not complement the scenario-based top-down approach. It is like the tail wagging the dog. It should be the converse: the bottom-up approach should be the starting point in hydrological risk management, which may be complemented by climate scenarios and economic optimality analyses. In highly vulnerable settings as they occur in developing countries, it is particularly important to perform bottom-up risk analyses, that is, to start from policy options and their risks, rather than to perform top-down modeling. Climate variability has the potential to produce Black Swan events for hydrology that are unexpected but have high impact from a societal point of view. Reducing the vulnerability and increasing the resilience of the system by a bottom-up approach leading to robust and flexible strategies will therefore be the hallmark of hydrological risk management in a changing world.

Acknowledgments

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5.02 State of the World's Water Resources

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5.02.1 Introduction

Water is widely recognized as a critical Earth resource that is essential for human prosperity and healthy ecosystems. Although over 70% of our planet is covered by water, only a small fraction is freshwater that is ready for human consumption (Falkenmark 1998; Falkenmark and Biswas 1995; Gleick 2003). Furthermore, freshwater resources vary widely both in space and time that is often in conflict with water demand. The staggering numbers of people lacking access to safe drinking water (1.1 billion) and proper sanitation (2.4 billion) are well documented (http://www.who.int/water_sanitation_health/hygiene/en), resulting in a loss of 2 million people per year (mostly children under the age of 5) due to diarrheal diseases (The 2 million lives lost each year because of water-borne diseases as a fraction of the global population (0.028%) is comparable to the impact of the 2003 heat wave in Europe causing 14 802 excess deaths [http://www.earth-policy.org/plan_b_updates/2006/update56] in France alone, with a population of 65 million (0.021%)). Less emphasized is the fact that the vast majority of people (900 million) suffering from water scarcity are extremely poor, living under the one-dollar-per-day poverty line (Rijsberman 2006), which represents an inequity gap between the top and the bottom of the population similar in magnitude as the difference between the top third and the wealthiest 1%.

The world population experiencing water scarcity is expected to increase both in absolute and relative numbers and possibly reach two-thirds of the total population in the next several decades (Shiklomanov 1990; Vörösmarty et al. 2000; Alcamo et al. 2000), dominantly due to population growth. Changing climate (in terms of shifts in the norms, e.g., average temperature or precipitation) will likely play a minor role (Fekete et al. 2010; Vörösmarty et al. 2000). While growing population always exacerbates water shortages, changes in average climatic conditions would have both beneficial and detrimental impacts. Anticipated changes in the tails will increase vulnerabilities to extreme events.

A recent study (Vörösmarty et al. 2010) assessing major threats to water resources from water security and ecosystems perspectives found that rich nations in general are better equipped to mitigate water scarcity and were able in the past to secure freshwater resources to meet their needs by investment in water infrastructure. Technically, any increasing demand for resources other than energy can be satisfied by investing more energy (Gever et al. 1986) either by exploring less readily available resources or replacing with substitutes. Water is not any different in this respect, and on a planet that is covered mostly by water, there are a variety of options to satisfy water demand either by recycling consumed water, transport water from long distances, or desalinate sea waters. From long-term sustainability perspective, the need to deploy energy-intensive technologies to secure water resources is alarming since energy sources (both renewable and nonrenewable) are clearly finite and represent a strict limit to how much energy can be employed to deliver water.

The same study (Vörösmarty et al. 2010) found that threats to ecosystems are poorly addressed in the developed world and developing countries with large remaining pristine river basins still have more healthy ecosystems than rich nations with significant engineering resources. The ultimate challenge of sustainable human development is to satisfy human needs and maintain healthy ecosystems in a changing climate that could reshape significantly the available water resources.

This chapter provides an overview of the current understanding of the spatial and temporal distribution of water resources contrasted with different water uses that are typically characterized as consumptive or nonconsumptive depending on whether the utilized water is released to the atmosphere or remains in liquid form and ultimately is returned to surface or subsurface water storage pools.

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5.02.2 Water Availability

Global water resource assessments have a long history dating back to the 1950s when Thornthwaite and Mather (1955) established the first estimates of key components of the continental water budget based on monthly average surface air temperature and precipitation records from over 14 000 meteorological stations worldwide (Legates and Mather 1992). Table 1 shows several estimates of global discharge fluxes to ocean from different authors since the mid-1970s.

While these estimates appear to show a wide spread (Schlosser and Houser 2007), the realistic estimates are reasonably narrow. With the exception of Korzoun et al. (1978), Oki et al. (1999), Grabs et al. (1996), Syed et al. (2010), and Haddeland et al. (2011), estimates fall within the 36 000–40 000 $km^3 yr^{-1}$ bounds that Fekete et al. (2002) argued as the plausible range based on the river discharge from available data archives.

Grabs et al. (1996) and Fekete et al. (2002) practically used the same set of discharge gauges (capturing 20 700 $km^3 yr^{-1}$ annual discharge) while monitoring ~50% of the continental land mass, which is ~70% of its actively contributing portion (Fekete et al. 2002). The difference between the two estimates arose from the assumptions about the ungauged land mass. Grabs et al. (1996) recognized that the monitored portion is about half of the total land mass and assumed that the runoff generated in the nonmonitored regions was equal to the monitored regions. Fekete et al. (2002) applied a water-balance approach to assess the discharge from nonmonitored lands and found that while 60% of the nonmonitored areas are actually too dry to maintain organized river systems and deliver significant amount of waters to oceans, the other 40% of the nonmonitored lands are actually more than twice as wet as the discharge monitored regions.

Estimates of Oki et al. (1995) and Syed et al. (2010) were both derived from the atmospheric budget based on the National Centers for Environmental Prediction (NCEP) reanalysis (Kalnay et al. 1996; Kistler et al. 2001), and the significant deviation from other estimates based on precipitation and discharge observations combined with terrestrial evapotranspiration estimates reflects more a deficiency in the NCEP reanalysis products than the uncertainties in global runoff estimates. The Syed et al. (2010) estimates also incorporated mass changes observed by the Gravity Recovery And Climate Experiment (GRACE) gravity-monitoring mission, but since the water storage change at annual time scales is normally considered negligible, this estimate is still primarily constrained by the inaccuracy of the NCEP reanalysis.

Table 1 Global river discharge to ocean estimates in cubic kilometers per year

Source	*Discharge*
Baumgartner and Reichel (1975)	37 713
Korzoun et al. (1978)	46 900
L'vovich et al. (1990)	39 700
Oki et al. (1995)	22 311
Postel et al. (1996)	40 700
Grabs et al. (1996)	42 700
Nijssen et al. (2001)	36 103
Fekete et al. (2002)	38 320
Dai et al. (2009)	37 288
Schlosser and Houser (2007)	36 000
Syed et al. (2010)	32 851
Wisser et al. (2010a)	37 405
Haddeland et al. (2011)	42 000–66 000

The NCEP reanalysis product is the result of applying the National Center for Atmospheric Research (NCAR)–NCEP operational weather forecast model in a data assimilation scheme, where the model predictions are constantly adjusted based on observed states of the atmosphere from various sensors (weather stations, balloons, and satellite data). The deficiency of the NCEP reanalysis is alarming since it reflects a general weakness in atmospheric models to realistically represent key components of the water budget. The poor representations of precipitation in global circulation models and their operational weather forecast siblings are well known (Ines and Hansen 2006; Sperna Weiland et al. 2010).

The most recent estimates by Haddeland et al. (2011) are disturbing for numerous reasons. This study was carried out as an international exercise by a number of research groups actively developing and using global land-surface (LSM) and hydrological (GHM) models. The 11 participating models were tested using the same meteorological forcing from the European Center for Weather Forecast ERA-40 reanalysis (Uppala et al. 2005) for the 1985–99 period. The reanalysis data were bias corrected based on Climatic Research Unit (CRU) air temperature, diurnal temperature range and wet days (New et al. 1999; Mitchell and Jones 2005), and precipitation from the Global Precipitation Climatology Centre's (GPCC) version 4 *full* product (http://gpcc.dwd.de).

The high discharge to ocean estimate can partly be explained by the high precipitation input that averaged 872 $mm yr^{-1}$ over the 1985–99 period. It is unclear how the ERA-40 reanalysis bias correction was carried out, but according to our own calculation the average precipitation over land from the GPCC v4 *full* gridded precipitation product is 819 $mm yr^{-1}$ so the forcing data were ~6% higher, which could lead to 10–12% more runoff alone. However, the elevated precipitation does not explain the 66 000 $km^3 yr^{-1}$ estimate, which is 60–70% higher than the plausible range between 36 000 and 40 000 $km^3 yr^{-1}$ based on gauged basins (Fekete et al. 2002).

It is hard to accept that hundreds of discharge gauges globally would have systematic low bias, but it is also infeasible that the ungauged regions (less than 30% of the actively contributing land mass) could produce three times or more discharge to the oceans than the monitored 70%. Besides the large bias in these model simulations the huge spread between models is also concerning. Prior to this study, global water resource assessments seemed to converge to the plausible 36 000–40 000 $km^3 yr^{-1}$ range, but this study shows enormous differences. If this level of model uncertainties in the modeling of the hydrological system alone is real, one has to wonder, if any of these models could be used to make realistic water resource assessments at global scale.

5.02.2.1 Contemporary Water Resources Variability

A number of studies have attempted to estimate the key components of the hydrological water budget, but less research has been done to assess its variability. A major roadblock in the accurate assessment of the time varying water budget is the lack of high-quality river discharge data that are the most accurately measured components of the hydrological cycle (Hagemann and Dümenil 1998; Grabs et al. 1996; Gutowski et al. 1997).

Probably, the most comprehensive analysis of available discharge records was carried out by Dai et al. (2009). They assembled publicly available discharge records from all over the world and performed a series of analysis to fill in data gaps (correlating discharge from nearby gauges, going back to available stage height records, relating basin-wide precipitation to discharge records). The remaining data gaps for the 1948–2004 period were filled in by linear regression between runoff estimates from the community land-surface model (CLM3) and observed discharge records. The resulting data set consisting 925 ocean reaching watersheds that covers 80% of the nondeserted, nonice and non-internal-draining areas capturing over 73% of the continental discharge into oceans is undoubtedly the most complete set of discharge records available today.

Dai et al. (2009) found that given the high interannual variations in runoff, detecting significant trends over periods of longer times are difficult. Nevertheless they found significant decreasing discharge trends in the Indian ($-5.4\ \mathrm{km}^3\,\mathrm{yr}^{-1}$) and Pacific ($-10.1\ \mathrm{km}^3\,\mathrm{yr}^{-1}$) oceans and an increasing discharge in the Arctic ($8.2\ \mathrm{km}^3\,\mathrm{yr}^{-1}$) that was consistent with previous studies (Peterson et al. 2002). They also found that in most river basins the land-surface model (CLM3) captures well the long-term runoff variations without representing irrigational water uptakes, which indicates that the impact of consumptive water use on the water budgets at large scales is still small (Milliman et al. 2008; Wisser et al. 2008, 2010a).

Wisser et al. (2010a) reconstructed the twentieth century hydrography solely by water balance estimates driven by precipitation and air temperature from the CRU of East Anglia (Mitchell and Jones 2005). They found that over the period of 1901–2002 (that the CRU data set represents) the annual runoff increased slightly by $11\ \mathrm{km}^3\,\mathrm{yr}^{-1}$, which is the equivalent of $0.03\%\ \mathrm{yr}^{-1}$ in normalized terms (with respect to the long-term average over the same period). Applying the *full* precipitation product from the GPCC (http://gpcc.dwd.de), Offenbach, Germany, in the same model from Wisser et al. (2010a) resulted in a declining trend with similar magnitude (Figure 1). Furthermore, a closer look at the time series of annual runoff during the 1901–2002 period reveals a slow increase ($17\ \mathrm{km}^3\,\mathrm{yr}^{-1}$) during the 1901–60 period followed by a more rapid decline ($52\ \mathrm{km}^3\,\mathrm{yr}^{-1}$) during the rest of the century. These separate trends are also present in the Wisser et al. (2010a) analysis. Similar trends in precipitation are characteristic features of both the CRU and the GPCC products with different magnitudes.

The trends based on GPCC precipitation in the normalized runoff (using the 1901–2002 mean runoff as a reference) by receiving oceans (Figure 2) largely agree with Wisser et al. (2010a), but a closer look reveals clear changes in the prevailing trends over time. Trends during the second half of the century have some irregularities, deviating from Dai et al. (2009). The most significant is the declining runoff in the Arctic, which contradicts a number of studies (Peterson et al. 2002; Dai et al. 2009). The rapid increase in the first half of the century is also suspect since river discharge records from Eurasian rivers suggest that the runoff was stable before 1950 and the discharge increase accelerated only after 1980 (see Chapter 5.26, Changing Discharge Patterns of High-Latitude Rivers). Rawlins et al. 2009 already recognized these inconsistencies and attributed the erroneous precipitation trends to changes in the monitoring network.

While identifying trends from both the discharge records and the water balance calculations appears to be difficult (Dai et al. 2009; Milliman et al. 2008), the water balance calculations are important tools to assess the interannual variability of the continental runoff (Table 2). Globally the continental runoff could vary between 88 and 110% around the long-term mean discharge ($37\,786\ \mathrm{km}^3\,\mathrm{yr}^{-1}$ in the GPCC precipitation simulation) in response to 95–105% variation in global precipitation ($789\ \mathrm{mm\,yr}^{-1}$). According to water balance calculations, Australia (including New Zealand and several surrounding islands) experiences the widest range (65–209%), where the extreme high runoff occurred in 1974 when the annual runoff

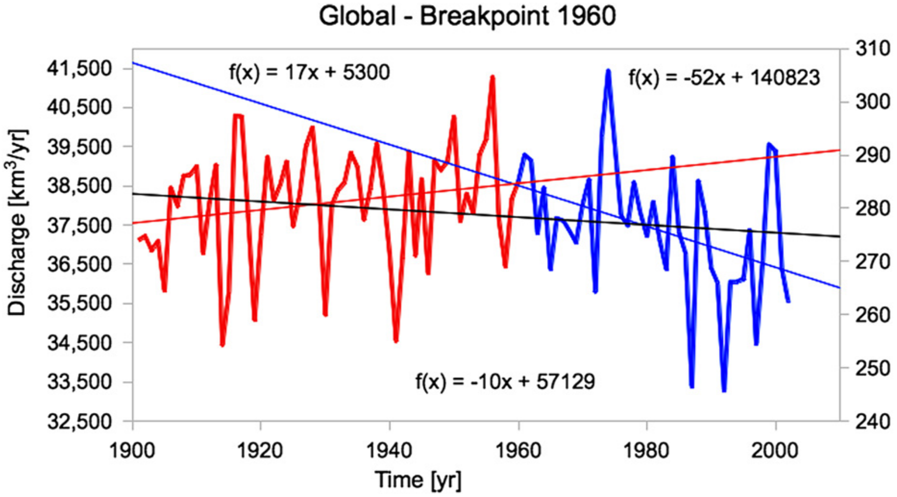
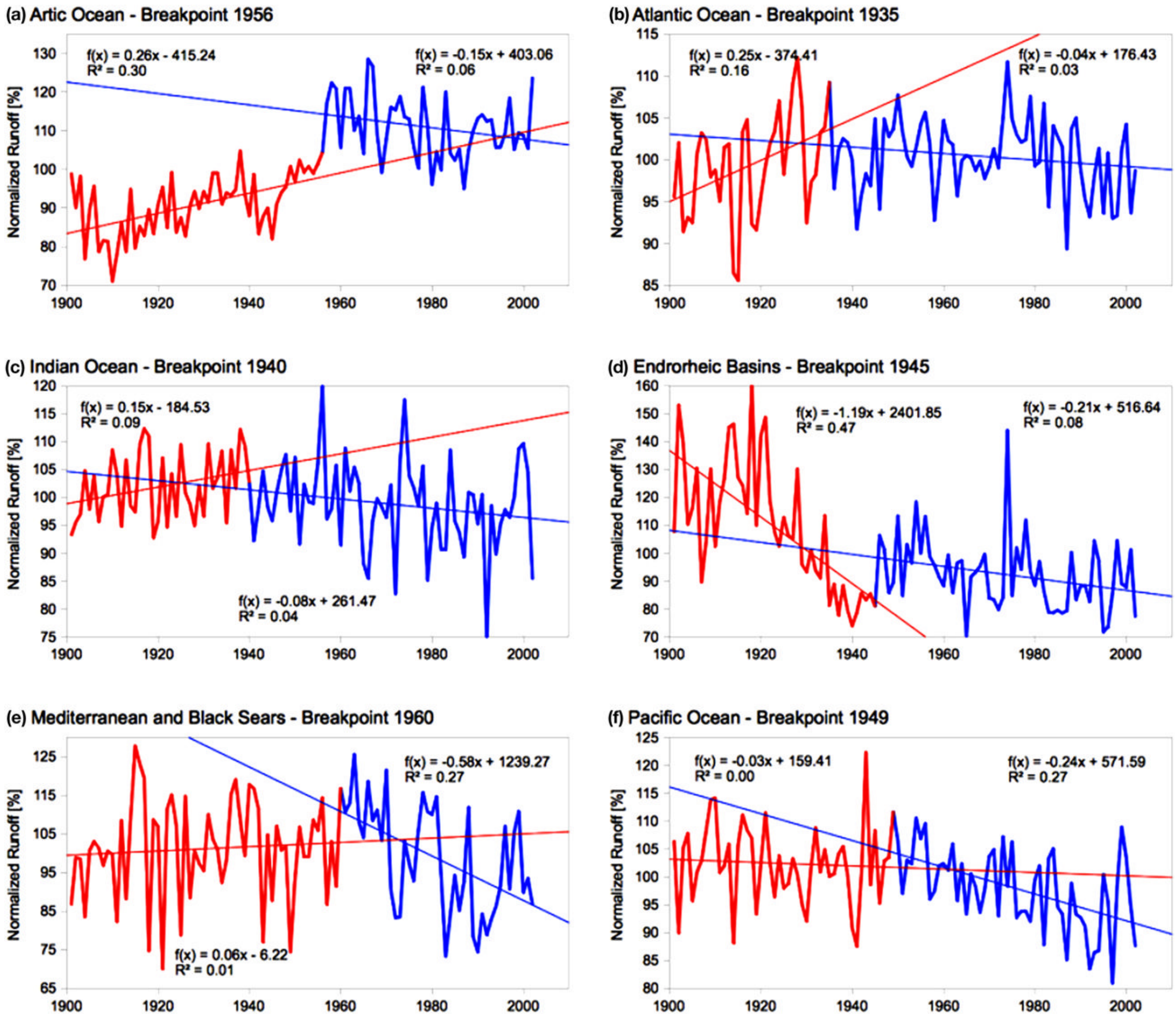


Figure 1 Twentieth century global runoff trends. The global runoff shows a $10\ \mathrm{km}^3\,\mathrm{yr}^{-1}$ decline over the 1901–2002 (thin black line), which is the result of a $17\ \mathrm{km}^3\,\mathrm{yr}^{-1}$ increase from 1901–60 (thin red line) followed by a rapid $52\ \mathrm{km}^3\,\mathrm{yr}^{-1}$ decline (thin blue line) after 1960.


(a) Artic Ocean - Breakpoint 1956

(b) Atlantic Ocean - Breakpoint 1935

(c) Indian Ocean - Breakpoint 1940

(d) Endrorheic Basins - Breakpoint 1945

(e) Mediterranean and Black Sears - Breakpoint 1960

(f) Pacific Ocean - Breakpoint 1949

Figure 2 Normalized runoff trends by receiving oceans.

was more than twice (2386 $km^3 yr^{-1}$) the long-term average (1144 $km^3 yr^{-1}$) in response to 922 $mm yr^{-1}$ annual precipitation, which was 41% above normal (652 $mm yr^{-1}$). This degree of runoff response magnification to increased precipitation might be partially due to deficiencies in the water balance formulation, but the tendency of disproportional increase in runoff due to increased precipitation is still a characteristic of the runoff generation processes (Fekete et al. 2004). In general, the water balance model runoff response is consistent with the reported runoff elasticity in the literature (1% change in precipitation causing 2–3% change in runoff) (Chiew et al. 2006; Fu et al. 2007; Sankarasubramanian et al. 2001).

5.02.2.2 Future Water Resources

Water resources under future climatic conditions are major concerns in terms of climate vulnerability. A number of studies attempted to assess changes in water resources under future demographic and climatic conditions (Alcamo 2005; Arnell 1999; Arnell and Liu 2001; Fekete et al. 2010; Vörösmarty et al. 2000). The inherent uncertainty in these studies comes from the inevitable reliance on global circulation models that have limited skills in even reproducing present day climate (Stephens et al. 2010).

Climate models predict more precipitation globally under future climatic conditions, which, in the models, is more pronounced over oceans than over land (Arnell 1999), but show some agreements regionally (more precipitation in the tropics and at high latitude and a decline in precipitation in the Sahel region) (Allen and Ingram 2002). The competition between elevated evapotranspiration due to higher air temperature and increasing precipitation would dictate whether particular regions experience an increase or a decrease in water resources. It is important to recognize, of course, that the climate model regional predictions of changes in weather and other climate statistics have not been shown to be skillful in hindcast predictions with these models (Pielke and Wilby 2012).

Table 2 Continental discharge/runoff variations[a]

Region	Discharge ($km^3 yr^{-1}$)	Runoff ($mm yr^{-1}$)	Normalized minimum (%)	Normalized maximum (%)
Africa	5557	185	72	125
Asia	11 932	268	80	120
Australia	1144	139	65	209
Europe	2041	201	69	136
North America	5693	232	84	120
South America	11 419	636	80	113
Global	37 786	278	88	110

[a] *Annual discharge from continents along with average annual runoff is given in the first two columns along with normalized range of discharge/runoff fluxes referenced to the 1901–2002 long-term average.*

A recent study by Fekete et al. (2010) carried out water balance estimates based on Millennium Ecosystem Assessment climate scenarios. Climate scenarios under present and future conditions (centered around 2030 and 2050 referred as +30 and +50 year sensitivity experiments) were generated by the Integrated Model to Assess the Global Environment (IMAGE v2.4) (Bouwman et al. 2006). The future scenarios followed the Millennium Ecosystem Assessment (MEA) story lines (Alcamo 2005): Adapting Mosaic (AM), Global Orchestration (GO), Order from Strength (OS), and Technogarden (TG) representing different human development strategies with respect to socioeconomic trends (globalization or regionalization) and environmental management (proactive or reactive). Climate forcings (air temperature and precipitation) from the IMAGE model were used in a revised version (Wisser et al. 2010a,b, 2008) of the Water Balance/Transport Model (WBM/WTM) by (Vörösmarty et al. 1989, 1998) incorporating key human alterations (irrigation and reservoir operations) to the water cycle to assess changes in hydrography.

The results of this study are summarized in Figure 3. The first two rows (Figure 3(a)–3(f)) show the latitudinal anomaly characteristics of air temperature and precipitation under present and future conditions. Temperature anomalies for the twentieth century (Figure 3(a)) based on hundred-year gridded data from the CRU (Mitchell and Jones 2005; New et al. 1999) (maximum and minimum averaged by latitude shown in solid line) envelop almost entirely the elevated temperature in the +30 years experiment (Figure 3(b)). The projected temperatures step out from the twentieth century climate variability under most of the Millennium Ecosystem Assessment (MEA) scenarios only by +50 years experiment (Figure 3(c)).

In contrast, the precipitation (which goes both up and down by latitude with respect to the twentieth century climatology (Figure 3(d)) unlike air temperature that only goes up at all latitudes) stays well within the standard deviations (shown as dotted line) of contemporary precipitation. The different development strategies have marginal effects on future precipitation (Figure 3(e) and 3(f)), while significantly different deviations from contemporary air temperature emerge according to the +50 years experiment (Figure 3(c)).

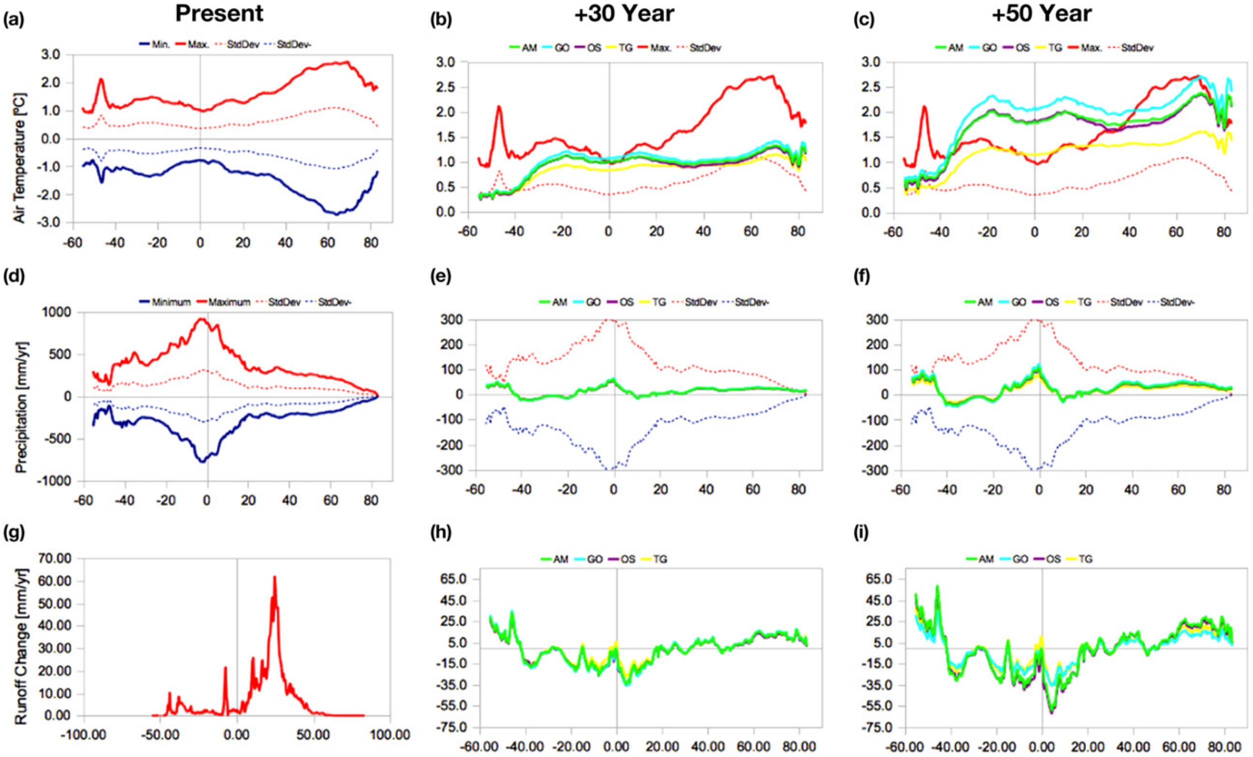


Figure 3 Millennium Ecosystems Assessment Scenarios. The top two panels show the latitudinal deviations of annual air temperature and precipitation averaged by latitude from the long-term mean according to the CRU time series. The second and third rows show the air temperature and precipitation change (respectively) by latitudes for +30 and +50 year sensitivity experiments relative to contemporary (year 2000) climate. Reproduced from Fekete, B. M., D. Wisser, C. Kroeze, E. Mayorga, L. Bouwman, W. M. Wollheim, and C. J. Vörösmarty, 2010: Millennium ecosystem assessment scenario drivers (1970–2050): climate and hydrological alterations. *Glob. Biogeochem. Cycles*, **24**.

The runoff response to changing climates (Figure 3(h) and 3(i)) differs as a function of latitude. At low latitudes, the increased evapotranspiration as a result of the elevated temperature dominates, which offsets the increased precipitation, resulting in a reduction of runoff in the water budget. At higher latitudes that precipitation increase plays the dominant role yielding more runoff.

Figure 3(g) shows the difference in runoff by latitude under present day climatic conditions turning the human alterations on and off, indicating that the impact of contemporary consumptive water uses is already in par with possible changes in the hydrological cycle due to climate. This study confirms the results of studies by both Arnell (1999) and Vörösmarty et al. (2000) that changes in the norms of key climatic variables such as air temperature and precipitation will have both negative and positive impacts on water resources, while direct impacts of water use on water availability would be exclusively negative.

None of these studies were able to address the adverse impact of the anticipated increase in extreme events. Current-generation climate models are not really suited for such studies since they are often limited to coarse time (monthly) and spatial scales (25–300 km) (Wilby 2010). They also lack the ability to replicate subgrid scale processes, complex topography, known lapse rates, and local snow–ice feedbacks (Wilby 2010), which are all critical in capturing high-frequency signals.

5.02.3 Water Use

Global estimates of water use agree that the dominant utilization is irrigation (Rosegrant et al. 2002; Döll 2002), but the actual proportion has significant uncertainties between 70 and 90% of the total water use. While irrigational water use is primarily consumptive and affects the quantity of water resources, other water uses (domestic, industrial, or agricultural) are typically nonconsumptive, impacting water quality.

5.02.3.1 Consumptive Use

Consumptive water use is estimated to range between 1200 and 1800 $\mathrm{km^3\,yr^{-1}}$ (Döll 2002; Vörösmarty et al. 2005), which is about one-third of the 6800 $\mathrm{km^3\,yr^{-1}}$ freshwater used for food production (both irrigated and rain fed) (Rockström et al. 2007). Additional 2200 $\mathrm{km^3\,yr^{-1}}$ freshwater will be needed to alleviate hunger in the next decade to accomplish the United Nations' Millennium Development Goals. This increase in freshwater appropriation can be met partially by an additional 270 $\mathrm{km^3\,yr^{-1}}$ irrigation (Rockström et al. 2007). The actual irrigational water withdrawal is higher (2500–3200 $\mathrm{km^3\,yr^{-1}}$) (Hanasaki et al. 2008; Döll 2002; Wisser et al. 2010b) than the estimated consumptive water use (1200–1800 $\mathrm{km^3\,yr^{-1}}$), but a significant portion of the irrigated water returns to surface and subsurface water bodies.

Agricultural water use traditionally was equated with irrigational water uptake, but more recently researchers started to argue that from food production perspectives all the waters that the crops utilize should be accounted for (Rockström et al. 2007; Rost et al. 2008). Irrigational water use is often regarded as blue water and rain-fed agricultural water use is termed green water. Green water use does not necessary affect the overall water budget of a region in a sense that conversion from natural ecosystems to cropping plants may actually decrease evapotranspirational water losses and increase runoff particularly when forested lands are replaced (Coe et al. 2011; Findell et al. 2006).

Accounting for green water is more important when crop trading is considered, which can be viewed as a form of water trading. Crops produced in water-rich areas are viewed as virtual water transfers that can alleviate pressure on water resources in water-deprived regions.

5.02.3.1.1 Blue Water

Consumptive agricultural water use is still a small fraction of the continental runoff (Döll 2002; Rockström et al. 2007), but occurs in water scarce areas, where irrigational water use often competes with other sectors (municipal and industrial) and ecosystems. Only one-fifth of the agricultural lands are irrigated, yet they provide 30–40% of the global food production (Döll 2002; Rost et al. 2008). This higher contribution is partly due to intensified agriculture, which relies more heavily on fertilizers, pesticides, and high-yield crop varieties, referred to as 'green revolution,' but partly due to eliminating the potential of crop failures in drought conditions.

Irrigated agriculture is clearly an important means to mitigate climate vulnerability at the price of significant investment in the necessary engineering infrastructures and severe alteration of the hydrological system. Perhaps one of the most extreme examples of intensive engineering is the Colorado river systems, which provide water to five states within the Colorado basin, largely for irrigation and partially for municipal water use (Figure 4) besides one-third of its water being transferred to neighboring river basins.

Besides interbasin transfers, irrigational water demand is often satisfied from groundwater sources. In the United States, 65% of the irrigated water is drawn from groundwater (Pimentel et al. 2004), and similar ~50% groundwater abstractions for irrigation are reported in India (Singh and Singh 2002). A significant portion of these water abstractions is withdrawn unsustainably from deep aquifers, resulting in steady drops in groundwater levels (Wada et al. 2010; Konikow 2011).

Several authors attempted to estimate the rate of unsustainable water extractions from deep aquifers, but these estimates show a wide spread. Vörösmarty et al. (2005) suggested that 16–33% (400–800 $\mathrm{km^3\,yr^{-1}}$) of the agricultural water withdrawal is extracted unsustainably. Rost et al. (2008) estimated the consumptive water use assuming no limit on irrigation (IPOT 2534–2566 $\mathrm{km^3\,yr^{-1}}$) versus under resource limitations (ILIM, 1161–1249 $\mathrm{km^3\,yr^{-1}}$), when irrigation is constrained to the available renewable water resources and suggested that the difference between the two estimates (1400 $\mathrm{km^3\,yr^{-1}}$) would need to come from nonrenewable or nonlocal supplies via interbasin transfers. They suggested that the difference between this estimate and that from Vörösmarty et al. (2005) primarily stems from the differences in their search algorithm to identify renewable water resources before assuming that the irrigational water demand was satisfied from nonrenewable sources. Rost et al. (2008) also estimated that only 730 $\mathrm{km^3\,yr^{-1}}$ is consumed (of the 1400 $\mathrm{km^3\,yr^{-1}}$ abstraction) and the rest actually returns to surface waters. Wada et al. (2010) using a similar global hydrological model

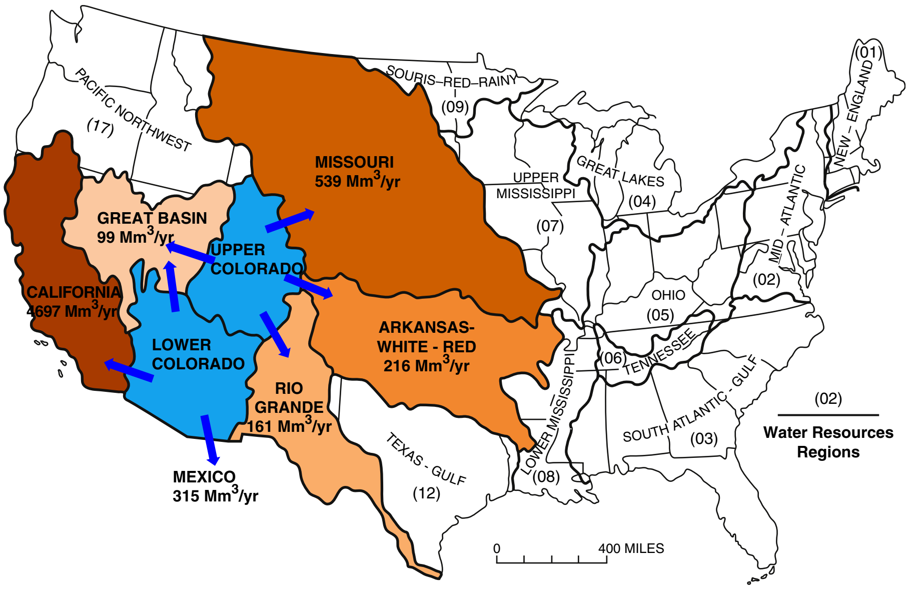


Figure 4 Interbasin transfers from the Colorado.

calculated 734 ($\pm$83) km^3 yr^{-1} groundwater abstraction for year 2000, of which 283 ($\pm$40) km^3 yr^{-1} came from unsustainable sources. Wisser et al. (2010a) arrived at 1200 km^3 yr^{-1} estimates of unsustainable water abstraction under contemporary conditions that rose from 220 km^3 yr^{-1} since the beginning of the twentieth century and concluded that over 55 000 km^3 water was withdrawn in the past 100 years.

Konikow (2011) recently questioned the high estimates and argued that previous assessments based on flux-based water budget calculations are inadequate in representing the true replenishment of groundwater aquifers and therefore they tend to overstate the magnitudes of unsustainable groundwater extractions. He carried out volumetric estimates from a variety of sources, including groundwater level measurements, pump age data, gravity change measurements from GRACE (Rodell et al. 2009; Famiglietti et al. 2011), and deterministic groundwater models, and found that groundwater depletion was significantly lower (145 km^3 yr^{-1}) averaged over the 2000–2008 period. He also estimated that the cumulative withdrawal since 1900 to 2008 was 4500 km^3, which could be responsible for more than 6% (12.6 mm) sea level rise during the same period.

Prorating the 55 000 km^3 groundwater depletion estimate from Wisser et al. (2010a) (which was consistent with Vörösmarty et al. (2005)) would suggest that over 73% of the sea level rise was due to unsustainable water withdrawals, which appears to be unrealistic. While the actual groundwater depletion is likely to be less than simple, flux calculations suggest that some of the differences between the volumetric and the flux estimates are likely to represent a major rearrangement where the water is stored since return flows from irrigated lands do not necessarily recharge the originating aquifers.

Slow recharging groundwater aquifers are undoubtedly unsustainable water sources for long-term operation of irrigation systems. The alternatives are operating reservoir, interbasin transfer, or desalination of seawater in coastal areas.

Reservoirs can capture excess water originated from the headwaters and control the timing of water availability. Over 45 000 large reservoirs (defined as higher than 15 m and exceeding 3 million m^3 volume) are in operation globally (Moore and Dore 2010) with 7000–8000 km^3 cumulative storage capacity (Vörösmarty et al. 1997; Lehner et al. 2011). About half of the world's large dams were built primarily to support irrigation (Richter et al. 2010) that directly contributes to 12–16% of the world's food production (WCD 2000), which is roughly one-third of the food produced on irrigated lands. Despite their obvious benefits, large dams are highly controversial in terms of the societal impacts (e.g., 40–80 million people were displaced by large dams), ecosystems degradation (Pringle et al. 2000; Dudgeon et al. 2006; Freeman and Marcinek 2006), and changes in riverine sediment delivery (Milliman and Syvitski 1992; Syvitski et al. 2005), with far reaching impacts on coastal areas. Large irrigation projects particularly in sub-Saharan Africa are often found costly and environmentally unsustainable (Ngigi 2003).

Interbasin transfers are highly intrusive alterations of the hydrological cycle with serious impact on aquatic ecosystems (Davies et al. 1992). While a large body of literature exist describing individual projects, no comprehensive study assessing its magnitude globally has been carried out yet. Interbasin transfers are almost epidemic, affecting river systems all over the world (e.g., Brazil (Carvalho and Magrini 2006), China (Berkoff 2003), India (Jain et al. 2005, 2008), South Africa (Swatuk 2010), and Spain (Ballestero 2004)). The Colorado river basin is probably one of the most extreme cases, where of the 18.44 km^3 yr^{-1} runoff (Blinn and Poff 1997) generated over 15% of the catchment area only 0.315 km^3 yr^{-1} crosses the Mexican border. While the majority of its water is consumed within the Colorado basin, over 31% (5.734 km^3 yr^{-1}) is transferred to neighboring basins (Figure 4).

Millions of small reservoirs, ponds, cisterns, tanks, and other microstorage facilities supplying water for very small areas (e.g., 1.5–50 ha in India (Gunnell and Krishnamurthy 2003)) are the basis for rainfall (or runoff) harvesting. Rainwater harvesting is an ancient technique (Oweis and Hachum 2006; Pandey et al. 2003), which has been a key in securing crop productions and improving yields (Wisser et al. 2010b). It is considered a compromise between green and blue water, which has less negative impact on riverine ecosystems and yet allows the utilization of local runoff. While rainwater harvesting has a rich literature, very few attempts has been made to quantify its significance globally (Wisser et al. 2010b).

A recent study by Wisser et al. (2010b) was probably the first that implemented small reservoir operation in a water balance model context (Vörösmarty et al. 1989, 1998) and concluded that these small-scale irrigations can provide 623–1122 km^3 water of their estimated 3250 $km^3 yr^{-1}$ irrigational water demand. Interestingly, their model simulations showed only a small decrease (from 49 to 44%) in unsustainable extractions, because harvesting rainwater largely prevented the recharging of the shallow groundwater that served as the secondary source of water resources before satisfying water demands from rivers and reservoirs and ultimately from unsustainable sources.

5.02.3.1.2 Green Water

Rain-fed agriculture provides the majority of the food production and will continue to do so (Rockström et al. 2007), yet their impact on water resources was neglected in the past. This negligence is not necessarily surprising, since rain-fed crops obviously replace natural vegetation, which also consumes water; therefore, green water use does not necessarily affect the overall water budget. Assuming that natural vegetation is in equilibrium with the available water, the intuitive expectation is that conversion to cultivation without irrigation is unlikely to increase evapotranspiration unless the planted crops have significantly better means to adapt to varying water availability. For instance, eucalyptus trees and other fast-growing exotic tree species could actually transpire more water than available from precipitation by reaching the groundwater with their deep roots and subsequently lowering the groundwater table (Calder et al. 1997).

Perhaps, the most important challenge in rain-fed agriculture is coping with climate variability. The crop yield improvement in the last several decades regarded as 'green revolution' was largely accomplished by reducing crop diseases through breeding more resistant crops or applying pesticides and supplying additional nutrients (Hazell 2002, 2009). For instance, the successful eradication of wheat rust, which had threatened wheat producers perennially before, via the introduction of resistant wheat varieties, resulted in the protection of 117 million hectare crop land (Chhetri and Chaudhary 2011). The introduction of inorganic fertilizers utilizing the Haber–Bosch process already has led to anthropogenic nitrogen fixation that surpassed the rate of natural processes (Rockström et al. 2009).

The introduction of more drought-resistant crops is widely viewed as the next critical step in food security (Cattivelli et al. 2008). Elevated CO_2 in the atmosphere accelerates plant growth (Daepp et al. 2000), particularly nitrogen-fixating plants, but water shortage can halt that acceleration (Aranjuelo et al. 2009). An increased CO_2 concentration is found to raise drought tolerance (Lin 2002).

Even if the introduction of drought-tolerant crops combined with the effects of CO_2 fertilization improves crop yields and reduces vulnerabilities to climate variations, regional crop failures and food shortages will remain inevitable, which can be mitigated by international food trade.

5.02.3.1.3 Virtual Water

Food trading is recognized as virtual water transfer (Ercin et al. 2009; Aldaya et al. 2010) and more recently as implied virtual land export (Fader et al. 2011). The term 'virtual water' was introduced by Allan (1993) almost two decades ago, but it took another decade to enter into global water resource assessments (Horlemann and Neubert 2002).

Obviously, not all food trading is driven by water resource limitations, and one could introduce analogous concepts of 'yellow' and 'red' radiation, reflecting the need for artificial light or heat to grow certain crops in cold climate. The 'yellow' and 'red' radiation and the corresponding 'virtual' radiation can explain the rationale of exporting high-value irrigated crops (e.g., olives, vegetables, and fruits) from dry countries (e.g., Israel) to water-rich regions (Canada or Northern Europe).

The differences in water demand to grow the same crops in different regions complicates further the virtual water accounting. For instance, growing wheat in France needs 1/10th of the water required to grow the same crop in Moroco (Mekonnen and Hoekstra 2010). Fader et al. (2011) presented a comprehensive water footprint accounting, which distinguishes green, blue, total, and external water footprint based on establishing green, blue, and total water balance and calculating green and blue water import and export. They concluded that virtual water trade is dominated by green water and food trading reduces water footprint, allowing the growing of crops where it is more efficient from water use perspective.

The promotion of international food trading contradicts the suggestions to increase local food productions often advocated by environmentalist groups, and flies against traditional desires for national self-sustainability that has led countries to go to the extremes like growing wheat in the deserts of Saudi Arabia.

Apparently, no study has been carried out yet to quantify virtual water trading as a means to increase food production's resiliency to climate variability. Just like long-distance power lines are a key for increased utilization of intermittent renewable energy sources such as wind or solar, water trade can clearly mitigate temporal water shortages due to regional crop failures. Negative examples exist, where trading agricultural products decreased resiliency in the exporting countries. Perhaps the most tragic example was the Ukraine famine in 1932–33, when millions died while the Soviet Union was still exporting grains despite poor crop production (Kuromiya 2008).

5.02.3.2 Nonconsumptive Water Use

Nonconsumptive water use, as its name implies, does not reduce water availability but typically degrades its quality. This water quality degradation is not taken into account adequately in most of the global water use estimates (Simonovic 2002).

Nonconsumptive water uses and the corresponding wastewater disposal have more severe environmental impacts than their volumetric accounting alone.

Traditionally, nonconsumptive water uses are categorized as industrial, domestic, or agricultural, although from the water resource perspective it might be more appropriate to distinguish the type of contamination regardless of its primary source. However, giving a full account of all the possible constituents far exceeds the anticipated extent of this chapter.

Solution to pollution is dilution. In other words, constituent loading to freshwater ecosystems are more harmful when they pass some critical concentration threshold. One could view wastewater disposal as a virtual water use, where certain amount of diluting 'clean' water is needed to allow the release of the wastewater. The amount of diluting water demand depends on the wastewater amount and the concentration of the constituents that the wastewater carries. Operating wastewater treatment facilities to remove some of the contamination before the wastewater is released helps to reduce the need for diluting 'clean' water, but at the cost of using energy in the water-treatment process.

A recent paper by Hoekstra and Mekonnen (2012) introduced the concept of gray water as a means to articulate water pollution in the context of unified water footprint accounting. They found that gray water is responsible for 15% of the total water footprint, which is the second largest after green water (at 74%) and higher than blue water (11%). Since green water dominantly replaces water uptake by natural ecosystems, this finding demonstrates that from the water resource management perspective water pollution from nonconsumptive use (gray water) is in the same magnitude as consumptive water use (blue water).

5.02.3.2.1 Domestic Water Use

Domestic water uses (just like energy use) are closely linked to wealth and human development. Figure 5 shows the per capita daily water use as a function of human development index (HDI). The HDI introduced by the United Nations Development Programme (UNDP 1990) combines various human development metrics (life expectancy, education, and income) as a single measure of human welfare. Similar to energy use and gross domestic product (GDP), domestic water use is closely linked to wealth and HDI. The poorest one-fifth of the population that lacks access to basic services such as electricity, clean water, and sanitation has significantly lower domestic water use than developed nations.

The cumulative curve of the population (green line) ranked by HDI in Figure 5 increases more rapidly than the cumulative curve of the domestic water use. Sudden jumps in both curves correspond to populous nations (e.g., India and China). The deviation between the cumulative population and domestic water curves reflects a serious inequity where three-quarters of the global population uses the same amount of water for domestic purposes as the remaining one-quarter. While better water management and improved water use efficiencies are keys to reduce water use in developed nations (Totten et al. 2010), developing nations with low domestic water use on the per capita basis will have nowhere else to go but to increase significantly their water use, and this increase undoubtedly will outpace any change in available water resource due to climate.

Perhaps a characteristic example where water resources are under serious stress is China, which has the same amount of water resources as Canada but 100 times the population (Wu et al. 1999). Putting it in deferent perspectives, China has 22% of the global population and 6% of the freshwater resources (Dabo and Hubacek 2007), which is distributed unevenly within the country. Half the population lives in North China, which has only 20% of the national freshwater resources (Dabo and Hubacek 2007). Rapid economic growth has led to a doubling of wastewater production in a decade from 1990 to 2000 (Wu et al. 1999). China already treats 47.5% of its wastewater, which is well above the 10% global average (Gao et al. 2008). Despite the reasonably high level of wastewater treatment for a developing country, 45% of the rivers surveyed

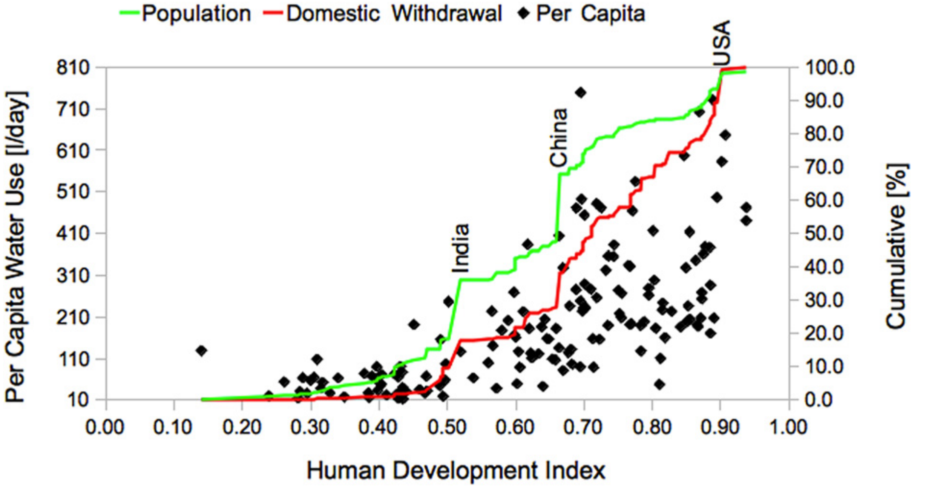


Figure 5 Domestic water use by human development index (HDI). The figure shows the relationship between per capita domestic water use (black diamonds) and HDI (left axis) contrasted by the cumulative population (green line) and per domestic water use (red line) ranked by HDI and expressed as the percent of the global total (right axis). Sudden jumps in both the cumulative curves correspond to countries with a large population.

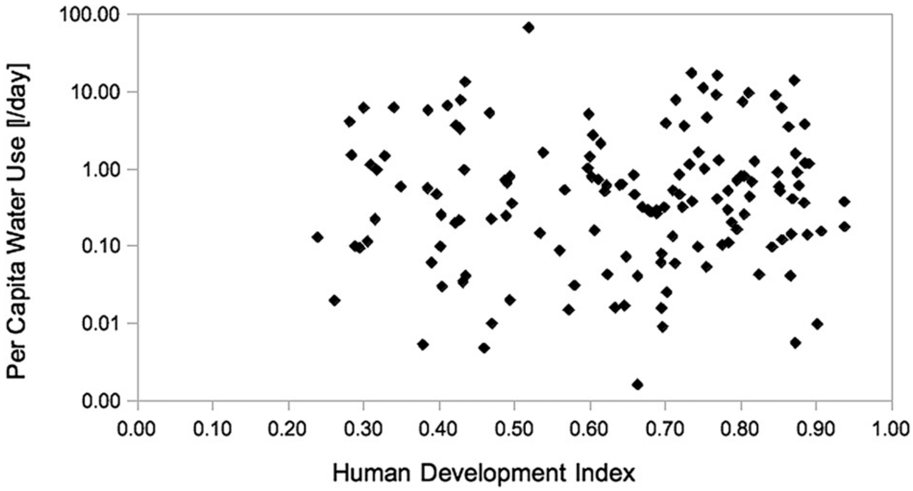


Figure 6 Industrial water use per capita as a function of human development index from Food and Agriculture Organization (FAO) Aquastat.

were polluted moderately to severely (Ministry of Environmental Protections 2009). China is going through a development path similar to that developed countries went through throughout the twentieth century, which severely impaired aquatic ecosystems before starting to invest in environment protection.

Countries need to reach a certain level of wealth before they can deal with environmental concerns following the environmental Kuznets curve (Dinda 2005), which leads to inevitable environment degradation before improvements.

Recent research by Vörösmarty et al. (2010) carried out global assessments of the various threats to riverine freshwaters, which is the dominant contributor to freshwater resources (World Water Assessment Programme 2009), and demonstrated that rich countries are able to reduce the threats to their water resources by investing in water infrastructure. These investments tend to deal with the symptoms rather than 'curing' the cause and often are inadequate to address the threats to biodiversity.

5.02.3.2.2 Industrial Water Use

Industrial water use differs from domestic water use only in the type of contaminants released in large quantities. For instance, accidental cyanide spills from goldmine operations have long-lasting effects on aquatic ecosystems (Gacsi et al. 2005; Lakatos et al. 2003; Shehong et al. 2005). Heavy metals and toxic chemicals in large quantities rarely originate from domestic sources.

Industrial water use per capita shows a wide spread among different countries and appears to be completely decoupled from human development (Figure 6). This decoupling probably reflects the tendency for poor countries to become exporters of more water-intensive raw materials and industrial products. As in the case of domestic water use, industrial wastewater either needs more diluting water when released into surface waters or needs to be treated, which is typically energy intensive.

A special case of industrial water use is water withdrawal for coolant for thermoelectric power plants (both fossil and nuclear powered). Cooling water is used both consumptively (when the water is evaporated in cooling towers) and nonconsumptively (when thermally 'polluted' water is returned to surface waters). While thermal contamination largely can be dealt with in a manner similar to chemical constituents, where the key is the availability of sufficient amount of diluting water, the challenges to secure cooling water demand will be undoubtedly exacerbated by global warming.

In the European Union, 43% of the water demand is for use as cooling water (Rübbelke and Vögele 2011), which is essential for power generation. The temperature differential between the power plants and their environment is an important factor determining power plant efficiency (Mideksa and Kallbekken 2010). A 1 °C rise in temperature could cause a small (0.45–0.8%) but not insignificant reduction in power plant efficiencies (Mideksa and Kallbekken 2010).

Heat waves that often coincide with prolonged droughts can severely compromise power generation at the time when demand for electricity is typically high. The 2009 heat wave in France caused cooling water shortages (Rübbelke and Vögele 2011), resulting in a loss of one-third of the nuclear power capacity, and France (which is normally an exporter of electricity) had to import from the United Kingdom. The 2003 heat wave led to a similar water shortage when 30 nuclear power plants had to reduce their electricity output (Rübbelke and Vögele 2011).

5.02.4 Conclusions

Water resources are under serious anthropogenic stresses already. While climate and particularly possible increase in extreme events would exacerbate the challenges to secure water for human consumption and maintain healthy ecosystems, the dominant pressure on water resources will remain as various human activities (consumptive and nonconsumptive water uses) directly affect the water cycle.

This pressure will only increase in most parts of the world where one-third of the population lives in conditions not very different from medieval Europe and another third has a living standard more close to life in the nineteenth century Europe or

North America. Improving efficiencies and better water management can reduce the anthropogenic stresses in developed countries. In contrast, the majority of the world's population has no other choice than to increase their 'footprint' in all aspects of resource utilizations (primarily their energy and water use) intensified by population growth as long as they aspire to have a comfortable life.

The lifestyle choices at the bottom one-third of the population are not whether they should take a shower twice a day or use a water-efficient shower head, but if they have to carry their cooking water on foot from long distance. The eradication of poverty, malnutrition, and illiteracy are not only a moral obligation to anybody who is concerned about inequity but also the ultimate path to stabilize population that is essential to sustainability.

According to recent projections by the United Nations (United Nations 2011), 42% of the global population already lives in countries where the fertility rate is below reproduction level and another 40% have intermediate fertility (2–3 children per woman). Only 18% lives in high-fertility countries, with more than three children. While large differences exist between countries because of cultural, ethnic, and religious circumstances, the main factors controlling the fertility rate are education and wealth (Shirahase 2000; Okazaki 1981; Shukla 1982). While the latter leads to increased life expectancy, which contributes to population growth, the lower fertility rates offset that rapidly.

The focus on climatic change apparently hijacked the attention to alleviation of hunger, providing access to clean water, and proper sanitation or improving education in the last two decades, which should have remained in the forefront in globally orchestrated actions to move human development onto a more sustainable path. The alternatives, burning food crops as transportation fuel, which drives up food prices, denying access to cheap energy to the poor as the unintended results of current policies in place to combat climate change, are not only failing but are also facing growing objections from the developing world. The path to sustainability is clearly an expedited economic growth in the developing world to shorten the rising trajectory of the environmental Kuznets curve, enabling developing countries to get on the declining environmental stress side sooner.

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5.03 Recent Trends in Regional and Global Intense Precipitation Patterns

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5.03.1 Introduction

5.03.1.1 Extremes in Precipitation

The term 'extreme' has two meanings, one of them is purely mathematical; for example, when we have a sample X(i), ($i = 1, 2, \ldots, n$) from an arbitrary distribution and the sample size is sufficiently large, the values at the distribution's upper tail more and more closely (asymptotically) follow the specific, narrow defined sets of distributions defined by the extreme value theory (cf., Coles 2001). Furthermore, the absence of precipitation (P) is quite common and under extremes at the low end of its distribution; we include prolonged intervals without P (including miniscule values) that are 'sufficiently rare.' Values at the tail of the probability distribution technically qualify to be considered as 'extremes.' However, there is no common agreement as to how far from the center of this distribution the 'extremes' lie. The definition of 'extreme' may well depend on the scientific, social, political, engineering, etc. application in order to evaluate the size of the 'extreme' we are looking for. Upper 5% of daily events, maximum annual value, etc. were frequently used in theoretical climatological assessments (e.g., IPCC 2007), but in other areas (e.g., hydrology, civil engineering, studying natural and anthropogenic hazards) the term 'extremes' has a *negative* connotation. It is more widely used to describe situations that cause damage that must be prevented, mitigated, and/or accounted for long-term planning such as construction of houses, bridges, other infrastructure, human health protection, and water management. Therefore, another definition of the extreme precipitation term is 'human-defined.' Nature knows no bad weather, but we as a society do. We consider each weather event that affects societal well-being (human health, harvest, flood, drought, water supply, property value, and infrastructure) as an extreme event. For the lower tail, the 'human-defined' sibling of the extreme term, drought, is measured by its impact on society and the environment.

While two approaches to introduction of the term 'extreme' are intertwined and coincide at the very end of the tails of precipitation distribution, different segments of the scientific community may focus on the term differently, which can cause confusion and/or misunderstanding. Some typical examples are as follows:

- A 2-inch daily rainfall event in the US Midwest might be categorized as 'extreme,' but under most circumstances a farmer would be grateful for this rainfall in the early summer.
- Classification of the upper 5% (or similar percentile) of rainy days as 'extremes' may be troublesome. For some, an 'extreme' connotes a sense of emergency, which may convey an inappropriate response.

These are legitimate concerns that warn 'pure' scientists not to juggle with the words but provide responsible answers on the topic that is of high-impact practical importance. Therefore,

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early on, when climatologists begin talking about increases in the high end of precipitation distribution (both frequency and intensity), they have used more neutral terms such as heavy, very heavy, and intense rain events (cf., Groisman et al. 2001). The term 'extreme rain event' was left to the events that would undoubtedly cause damage (e.g., rainfall of 150 mm d^{-1} or above). Not everyone accepted these terms, however. Moreover, not everybody was happy when instead of a selection between two categories, 'average' and 'extreme,' more sophisticated gradations were introduced that, in addition, vary between the research teams and regionally.

5.03.1.2 Definitions of Intense Precipitation

There is no way to avoid definitions of intense, heavy, very heavy, and extreme precipitation. Throughout this chapter we shall use several of them because these definitions are regionally specific and we are reviewing the results of different authors. We combine these definitions in Table 1 and each time these vague terms are used, we will clarify which definition was used and why.

There are two major types of definitions for the upper end of precipitation distribution. They can be partitioned in two classes associated with fixed thresholds (when a precipitation event is assigned to a particular class according to its absolute value, e.g., above 100 mm day^{-1}) and percentile defined thresholds (when a precipitation event is assigned to a particular class according to the frequency of its occurrence, e.g., once in 10 years or in the upper 1%, etc.). There are pro and contra reasons for selection of both types of thresholds. By selecting fixed thresholds for heavy precipitation of various intensities within a region, we initiate a preselection of locations where the micrometeorological conditions induce these events to be more frequent. Examples are sites located on windward slopes versus leeward slopes, coastal regions versus inland sites, etc. In extreme cases (which are exactly a target of our assessment), we may unintentionally include only a few locations where extreme precipitation occurs due to a combination of orography and atmospheric circulation causes (e.g., Yakutat, Alaska; foothills of the Himalaya Mountains). These results, when regionally averaged, do not represent the entire region but only its most humid areas. But, why is it worthwhile to look for extremes in the places where they do not (or are less likely to) occur? Using the percentile thresholds that are crafted individually for each location, we (with additional help of a carefully selected area-averaging procedure) receive a much better spatial representativeness for each region that accounts equally for precipitation extremes, for example, west and eastward of the Cascade Range in the Washington State. The last example clearly identifies one of the problems of the percentile approach: *it levels quantitatively disastrous and moderate precipitation events* that may negatively impact hydrological estimates of consequences of intense rainfall over the rough terrain (even while the places that are used to huge precipitation events may have an infrastructure that is designed to take it). The second problem with the percentile approach, when we are looking for 'real' extremes, is low accuracy of individual threshold estimates at the far end of the tail of the empirical distribution. At the right-side tail, the ranked time series provides a broad range of neighboring values that may differ from each other by scores of millimeters. Thus, the estimated 'threshold' carries with it both a peculiarity of the individual observing period at the site and a large random error of the estimate.

The discussion above suggests that by bypassing the percentile estimates, one can be better off by avoiding these two hidden caveats (leveling and low accuracy of the variables that are used only at an intermediate step of assessment). In the past, we experimented with and used both types of precipitation thresholds. In our opinion, the upper 5% of daily precipitation events (that across the conterminous United States on average occur 20 times per year and bring about 30% of annual precipitation totals) and/or a mean peak annual precipitation event do not qualify for the definition of 'extremes.' That is why 10 years ago we began using more neutral terminology 'heavy,' 'very heavy,' and 'intense' precipitation (cf., Groisman et al. 2001, 2005). The current concern is the possible changes in 'real' extremes, i.e., those that do endanger human life and/or well-being. These extremes are associated with very rare precipitation events.

We also have to admit that the ongoing (and projected) changes in precipitation do not fit simplistic scales when density distribution functions (normal distribution for temperature or gamma-distribution for precipitation) shift unchanged to the left or right with climatic change and

Table 1 Different definitions of precipitation events at the upper end of its distribution (fitted to the eastern two thirds of the conterminous US territory). Decimal points are introduced to accommodate the British Empire unit system (inches) used in the US Meteorological practice instead of the SI system

Term used to describe a precipitation event at upper end of its distribution	*Daily and multiday precipitation events with the totals above (or within) selected thresholds based on*	
	Absolute values	*Upper percentiles*
Above 10 mm[a]	Above 10 mm	n/a
Intense	Above 12.7 mm	Above the upper 25%
Heavy	[12.7–76.2 mm]	Upper 10–5%
Annual maximum event total[b]	From 10 to 300 mm	Approximately the upper 1%; may vary broadly
Moderately heavy	[12.7–25.4 mm]	n/a
Very heavy	Above 75 mm	Above the upper 1%
Extreme	Above 150 mm	Above the upper 0.1%

[a] *This characteristic (threshold) was introduced by Frich (1999) for global assessments of 'extreme' precipitation. It can be used in cold climates (e.g., in the Arctic) where totals above 10 mm are indeed rare.*

[b] *This characteristic is commonly used in the hydrological and civil engineering communities.*

interpretation of 'increased/decreased' areas under the tail parts of these distributions are interpreted as extreme precipitation patterns changes. These changes have been nonlinear in many parts of the world. For example, (a) the increase of totals and the events frequency at the high end of precipitation distribution may be accompanied with a decrease in precipitation totals (cf., Easterling et al. 2000; Sun and Groisman 2000; **Figure 1**, top); (b) interseasonal precipitation events distribution can change its grouping (Zolina et al. 2010, 2012; **Figure 1**, bottom; Groisman and Knight 2007, 2008); (c) changes in intense precipitation of different genera can have different directions and rates (cf., Kunkel et al. 2012; **Figure 2**); and finally (d) within the high end of precipitation distribution a different sign of changes can be observed (cf., **Figure 3**).

Figures 2 and 3, as well as **Figures 11, 14, and 15** require a more detailed explanation as to how they were originated. At all stations, we selected only days (events) with intense precipitation (as defined above). Groisman et al. (2012) sorted these events and grouped them within seven intensity ranges. Thereafter, all intense precipitation data within each daily or multiday intensity range were summed, along with the correspondent peak hour intensity, number of days, and number of hours with nonzero precipitation during these days. From these tallies we calculated mean precipitation duration, mean daily, and maximum hourly intensity for the days (events) with precipitation for each intensity category. The same approach was applied to subsets of data for (a) the first 31 years and the last 31 years of our sample; (b) the warmest 31 (30) years and the coolest 31 (30) years during the 1948–2009 (2007) periods using the mean annual surface air temperature of the Northern Hemisphere (TNH), CONUS, central United States (T_{CUS}), and Gulf of Mexico (T_{Gulf}) as guidance; (c) intense precipitation derived from tropical cyclones (TC) in the hurricane season (June–November) and intense precipitation that originated without direct TC impact; (d) intense precipitation during various phases of the El Niño–Southern Oscillation (ENSO) cycle (El Niño, Neutral, and La Niña months); and (e) various other combinations and complements, e.g., warmest years versus coolest years for TC-originated precipitation and, separately for precipitation that was not originated from TCs, warmest years versus coolest years only for the hurricane-free season, warm season (May–October) temperatures for T_{CUS} and T_{Gulf}, minimum and maximum temperatures for T_{CUS}, etc. This approach generated a suite of estimates of climatology and changes with time, global and regional temperatures, rainfall genera, ENSO, etc., of intense precipitation events.

5.03.1.2.1 Focus on the Warm Season and Intense Rainfall

Frozen precipitation is critically important for the land surface hydrological cycle delivering a delayed (after snowmelt) contribution to runoff. In many parts of the extratropics and in the mountainous regions, intense snowmelt represents a major source of spring extreme events (floods). However, it is not important how it was accumulated throughout the cold season (daily or in a few extreme snow storms). Only the snow water equivalent remaining in the spring snowpack matters. Additionally, interruptions to transportation and other aspects of everyday human life in the regions of unstable and/or ephemeral seasonal snow cover can depend on a snowfall deficiency. Therefore, extreme prolonged no-precipitation intervals in the cold season are of less consequence as compared to the warm season. In the warm season, prolonged intervals without rain affect the entire biosphere and several critical aspects of human activity (agriculture, water consumption, river transportation, and hydropower production to mention a few). Moreover, in the warm season in the extratropics, prolonged no-rain periods correspond to anomalously high surface air temperatures due to the development of the soil moisture deficit and suppressed evapotranspiration. Together, rain deficit and hotter temperatures feed back to each other strengthening the hardship of the drought conditions (Mescherskaya et al. 2011; Barriopedro et al. 2011; Dai et al. 1998, 2004; USCCSP 2009). We shall describe the changes in the no-rain periods duration in subsection 5.03.2.9 Prolonged No-Rain Periods.

5.03.1.2.2 Cautious Note

Here, we outline an important feature of combination of increase in both frequencies, prolonged no-rain intervals and intense rainfall. Quite often hydrologists and climatologists use *dynamic* characteristics of heavy/high rain/streamflow events, such as annual maximum of daily rainfall (or peak streamflow). If these characteristics show systematic changes (trends), they claim an increase in heavy (or extreme) precipitation and streamflow. If these characteristics do not have trends, they argue that nothing has been changed, e.g., with flood frequency (cf., Lins and Slack 1999; Hirsch and Ryberg 2011). However, in the regions where both ends of the precipitation (streamflow) distribution are affected, we can observe a high flow (rainfall total) year followed by a low flow (rainfall total) year and maximum annual rainfall or peak streamflow (as well as any *dynamically* defined characteristic of the distributions tail based on the data of a single year) will vary widely without showing systematic changes. In Section 5.03.2, we show that this is the case in some regions of the world (including the eastern part of the CONUS; cf., also Semenov and Bengtsson 2002).

5.03.1.3 The Role of Daily Data in Analyses

Daily data are the most widely available for analyses (cf., Global Historical Climatology Network-Daily, http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/). However, there is no reason to focus on single-day events only because intense precipitation events, except small-scale convective thunderstorms, have longer time scales. Even a short-term rain while beginning before the cessation time (which in many countries is not necessarily at midnight) can continue beyond this time, creating an impression that this is a 2-day-long event. To remedy this problem, different options were considered in studies of intense precipitation change. These include (a) consideration of 2-day (up to 5-day-long) rainfall totals (Kunkel et al. 1999, 2012; Groisman et al. 2001; Alexander et al. 2006), (b) a thorough documentation of the actual hours of begin and end of the rain events (Bonnin et al. 2004–2012), (c) assessment of the frequency of consecutive precipitation days (wet spells; Zolina et al. 2010, 2012) and consecutive intense rain days (intense rain events; Groisman et al. 2012), and (d) assessment of sequences of deep cyclones that one after another cross the region in a short time interval (e.g., in 2–3 weeks) with intense rains associated with them that first saturate soil and later fill all water bodies eventually causing disastrous floods (Lettenmaier et al. 2008; Kunkel et al. 2012).

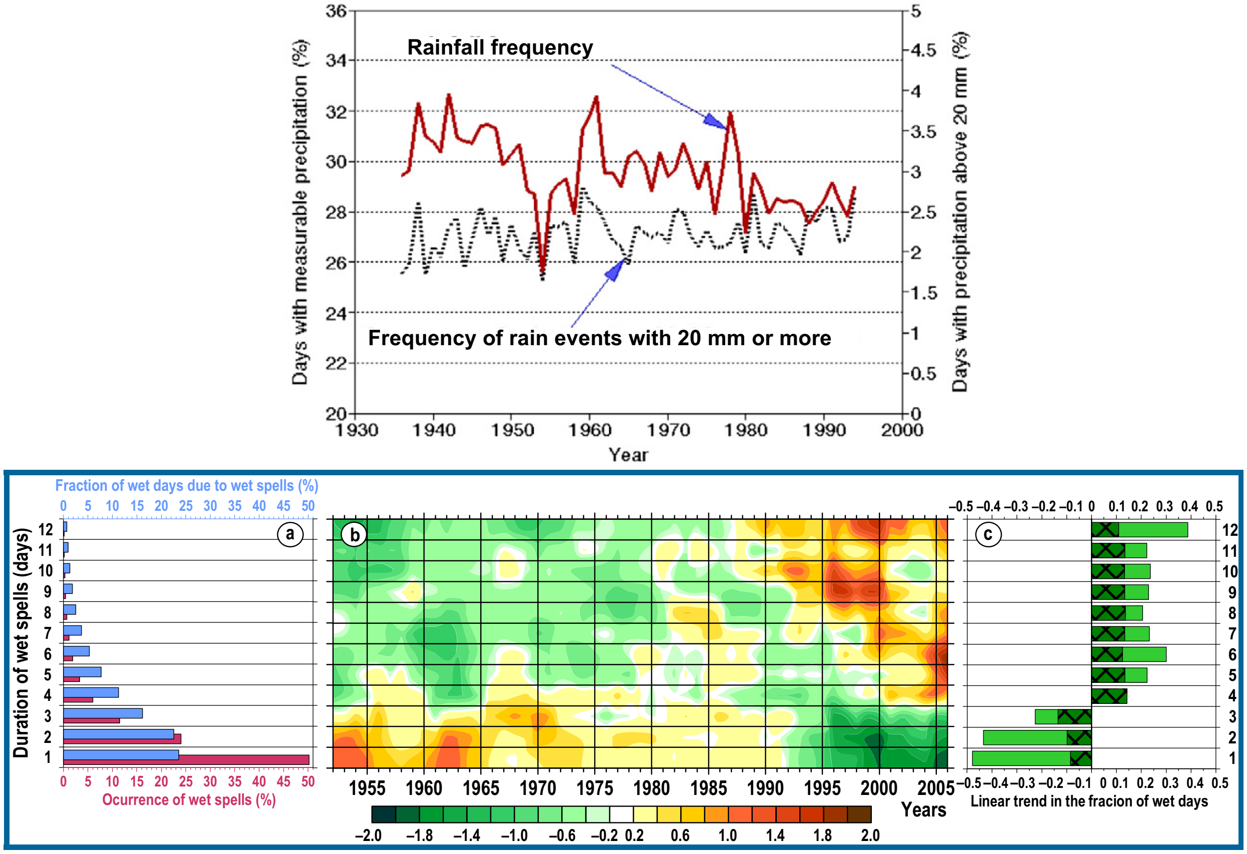

Figure 1 (Top) Summer frequency of rainy days and days with heavy rains over the Asian part of Russia (Sun, B., and P. Ya. Groisman, 2000: Cloudiness variations over the former Soviet Union. *Int. J. Climatol.*, **20**, 1097–1111.). In this part of the world, daily rainfall of 20 mm or above is considered as unusually heavy ('liven') and on average occurs approximately twice during the summer season. Bottom: Climatology of wet spells of different duration over Europe (a) climatology; (b) dynamics of changes with time; and (c) linear trends in the fraction of wet days (Adapted from Zolina, O., C. Simmer, S. K. Gulev, and S. Kollet, 2010: Changing structure of European precipitation: longer wet periods leading to more abundant rainfalls. *Geophys. Res. Lett.*, **37**, L06704. [Available online at http://dx.doi.org/10.1029/2010GL042468.]).

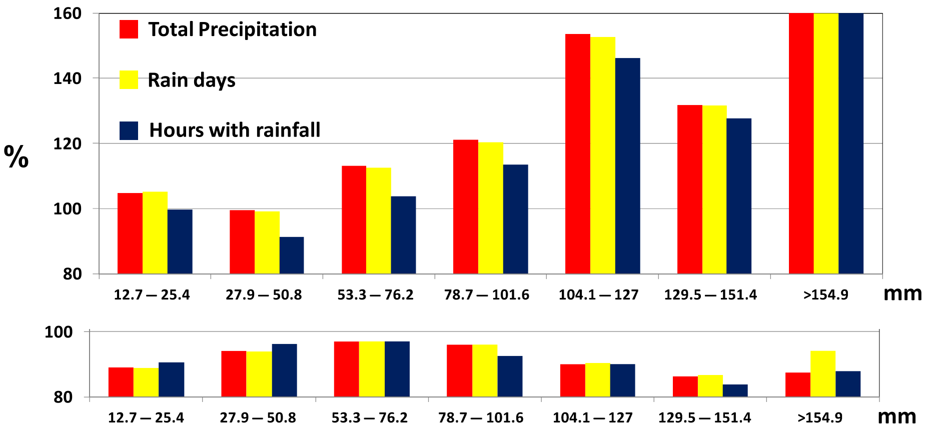

Figure 2 Comparison of intense precipitation characteristics during the June–November season over the southeastern United States associated with tropical cyclones (TC) for the 31 years of warmest and coldest Northern Hemisphere temperatures during the 1948–2009 period (top) and other not-associated with TC intense rainfall (bottom). Estimates of precipitation characteristics for these 31-year periods were averaged and their ratios (in percent per station) are shown sorted by day rainfall intensity ranges. The comparison shows that while the heavy rainfall characteristics associated with TC (up to extreme daily rain events above 154.9 mm) have increased over the southeastern United States during the last three decades, intense rain totals of other genera decreased (archive of Groisman et al. 2012).

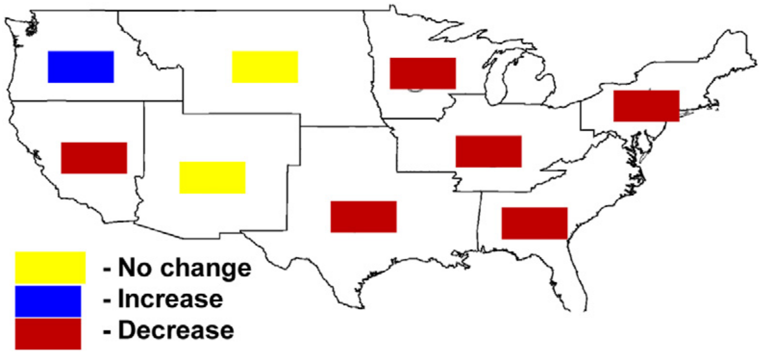

Figure 3 Changes with time, past three decades (1979–2009) versus previous period (1948–78) of the fraction of 'moderately heavy' precipitation (from 12.7 to 25.4 mm; or 0.5–1 inch) among all intense daily rain events above 12.7 mm over the contiguous United States. Annually among all daily rain events over the CONUS, 'intense' events (i.e., above 12.7 mm) comprise 25% of all days with precipitation but deliver more than 70% of rainfall. Among all intense events, days with moderately heavy precipitation are a majority (~75%) and deliver slightly more than a half of precipitation totals. The fraction of moderately intense precipitation within the intense precipitation spectra is shown to decrease over most of the CONUS (archive of Groisman et al. 2012). At the same time, very heavy precipitation is increasing over the eastern two/thirds of the CONUS (Groisman et al. 2004; USCCP 2009).

In Section 5.03.2, we present the observed changes in extreme precipitation during the past 50 years over the global land areas. To document 'observed' changes in rare precipitation events (extreme precipitation), one has to rely upon dense networks of many thousands of stations with long-term daily and hourly precipitation time series. However, these networks do not exist (or are not available to us) in some parts of the world. Therefore, referring to changes over 'global land,' we shall focus mostly on the extratropical land areas that are better covered by observations and on the regions/nations that openly share their data sets with the international scientific community. For some countries (e.g., for China, South Africa, and Japan), we are still able to perform our assessment using findings of national climatologists and hydrologists who have unrestricted access to the richest national hydrometeorological archives (cf., Zhang et al. 2011). For other countries (e.g., Poland), the international data centers either have no access to the volumetric national meteorological data or the national climatologists do not have permission to view and assess the complete daily data of the national hydrometeorological archive. Therefore, we had to omit the territories of these countries from consideration.

5.03.2 Observed Changes in Extreme Precipitation during the Past 50 Years over the Globe

5.03.2.1 Instrumental Precipitation Data Availability and Its Impact on Intense Precipitation Analyses

Each empirical study of extreme precipitation over a given region requires a dense network of meteorological stations (i.e., a network with high spatial resolution) with long-term precipitation time series at daily or sub-daily temporal resolution. There are several reasons for this requirement:

- A small scale spatial resolution of *some* precipitation extreme events (e.g., rainfall from summer thunderstorms has a typical radius of correlation of ~10 km; cf., Gandin et al. 1976). A sparse network of point measurements can easily miss the intense rainfall event or provide biased information about its peak intensity.
- Duration of intense rainfall or an intense phase of the prolonged rain event may be quite short (in many cases only a few hours) and assessment of precipitation totals for longer periods, e.g., monthly totals, may miss most of the features that make extreme precipitation so dangerous by causing flash floods in both urban and natural environments (cf., Changnon and Westcott 2002; http://www.nws.noaa.gov/hic/flood_stats/Flood_loss_time_series.shtml; Villarini et al. 2009; Robinson et al. 1998; Smith 2003). Furthermore, even the most violent rainfall can follow or be preceded by prolonged dry weather conditions and thus be virtually unnoticed within the totals.

Therefore, advances in accumulation and broad dissemination of the regional datasets that possess the above-mentioned properties closely correlate with our ability to document extreme precipitation events and to estimate their frequency, intensity, and changes in time and space.

As a vivid example, below we describe advances in studies of intense precipitation over the continuous US during the past 15 years. These studies used different methods and databases (Karl et al. 1997, 2009; Karl and Knight 1998; Easterling et al. 2000; Kunkel et al. 2003, 2007, 2010, 2012, 2013; Groisman et al. 1999, 2001, 2004, 2005; USCCSP 2009). The common feature in these data sets was the aggregation of precipitation to daily totals because, initially, there were no other reliable sources of climatological information on precipitation changes. The US Historical Climatology Network (that included initially 182 stations with daily data and now more than 1200 stations; http://cdiac.ornl.gov/epubs/ndp/ushcn/ushcn.html) was used by Karl and Knight (1998), Groisman et al. (1999), and Easterling et al. (2000) to assess the upper fifth percentile of stations' daily totals, the number of days with precipitation above 50.8 mm, and the changes in parameters of precipitation distribution with time. When the major archive of daily cooperative (COOP) stations was updated backward from 1948, the US climatologists were able to employ about

6000 daily time series over the United States and assess the century-long changes in very heavy precipitation events (in the upper 0.3 percentile of the precipitation distribution; cf., Groisman et al. 2004, 2005; USCCSP 2009). At each step, the advance was defined by new digital data sets of scientific quality that became available at that time and societal demand fueled by accelerated climatic changes and GCMs projections. The current concern is the possible changes in 'real' extremes, i.e., those that do endanger human life and/or well-being. These extremes are associated with very rare precipitation events. For example, days with rainfall totals above 154.9 mm over the hourly precipitation data (HPD) stations of the CONUS and US Midwestern states occurred once per 60 and 135 years, respectively. Using two independent precipitation data sets (HPD and COOP) and using the data only after World War II (which are much more numerous), it became possible to analyze the changes in the occurrence of these extreme events (Groisman et al. 2012).

Precipitation is the most closely monitored meteorological variable. The authors of the World Water Balance Assessment (WWB 1974) used climatological data from more than 100 000 individual rain gauge sites for their Assessment. At that time, focus was on monthly and longer time scales (cf., Legates 1987), and, to date, the major international center for precipitation data dissemination, Global Precipitation Climatology Center (Beck et al. 2005; http://gpcc.dwd.de/), archives and disseminates only the monthly precipitation data of approximately 45 000 stations. These data are disseminated in the gridded format due to restrictions imposed by the National Weather Services. Due to these restrictions, from present up to the last decade, daily data were infrequently used for large-scale precipitation change studies beyond the national boundaries. They remained preserved in different national archives worldwide. Since that time, attempts to assess precipitation changes at the daily and/or sub-daily time scales still have to rely on much smaller data collections. For example, the German and Mexican national archives store precipitation data from more than 7000 and 6000 stations, respectively, but they have not yet been tapped for international climate change assessments. For other nations, the situation is similar. An attempt to change this situation was launched several years ago with the establishment of the Global Historical Climatology Network-Daily (GHCN-Daily). Figure 4 shows the map of the meteorological stations density available in GHCN-Daily data collection for the past 60 years. This data set inherited all daily precipitation information available in the United States, Canada, and Australia, as well as several other national archives. The densest historical station networks come from the United States, Canada, and Australia – a reflection of the comprehensive contributions from these countries to GHCN-Daily. Nevertheless, Brazil, India, and South Africa have also contributed records from very dense national precipitation networks. For Europe, Russia, and China, the network contains only the stations designated for the international exchange by the national meteorological services of these countries.

GHCN-Daily is comprised of daily climate records from numerous sources that have been integrated and subjected to a common suite of quality assurance reviews (http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/). The data set contains records from over 75 000 stations in 180 countries and territories. Numerous daily variables are provided, including maximum and minimum temperature, total daily precipitation, snowfall, and snow depth; however, about two thirds of the stations report precipitation only. The GHCN-Daily dataset is regularly reconstructed (usually every weekend) from its 20-plus data source components to ensure that GHCN-Daily is generally in sync with its growing list of constituent sources. During this process, quality assurance checks are applied to the full dataset. The interval covered by GHCN-Daily station records varies from less than 1 year up to over 175 years, with the average precipitation record lasting about 33 years. The updates are routinely conducted but with delays for most of the globe except the CONUS. The European, Australian, and Canadian data in GHCN-Daily are updated monthly, but for other countries the delays in the latest daily data can be substantial. Most of the new results presented below will be directly or indirectly based on GHCN-Daily. Under indirect use we mean the use of updated national data sets (e.g., for Russia and Mexico) that are currently in preparation for open access through GHCN-Daily but have already been used in our analyses. Included with results of analyses of intense rainfall, several national and regional analyses of changes in heavy and extreme precipitation will also be provided. At present, large-scale analyses of heavy (extreme) precipitation changes at the sub-daily (hourly) time scale are available only for the conterminous United States where a dense network of hourly precipitation (HPD; Figure 4(b)) has been operational for the past 100 years, and these data (so far, since 1948) have been recently digitized.

5.03.2.2 Instrumental Precipitation Data Problems across the Globe

Changes (especially at extreme intensities) fortunately are mostly unaffected by the impact of numerous changes in precipitation instrumentation and observational practices. The most serious problem that causes biases in measured precipitation is wind-induced turbulence over the gauge orifice (Sevruk 1982; Goodison et al. 1998; Adam and Lettenmaier 2003), which for intense rainfall can be ignored starting with the rate of above 2 mm h^{-1} (Bogdanova 1966; Sevruk 1982). For intense snowfall, the impact of wind on the rain gauge catch can be substantial (Figure 5). Therefore, traditionally when studying the precipitation changes in the regions with a substantial fraction of frozen precipitation relative changes are assessed, i.e., changes expressed in percent of the long-term mean or in percent of standard deviation, changes in return periods, etc. (cf., Karl and Knight 1998; Stone et al. 2000; Førland and Hanssen-Bauer 2000; Kattsov and Walsh, 2000; Zhai et al. 2005; Kunkel et al. 2009; Zhang et al. 2010).

Due to a greater ability of the warm atmosphere to hold moisture compared to the cold atmosphere, the highest values of precipitation over most of the globe are observed in liquid form and the focus on intense and extreme precipitation in this chapter allows us to skip the still unresolved issues of accuracy of frozen precipitation measurements as well as systematic changes in their biases. Instead, we describe two somewhat related problems in liquid precipitation measurements that can affect estimates of intense precipitation changes. The sensitivity of the rain gauges, i.e., their ability to report the lowest amounts of precipitation, can unexpectedly affect statistics of

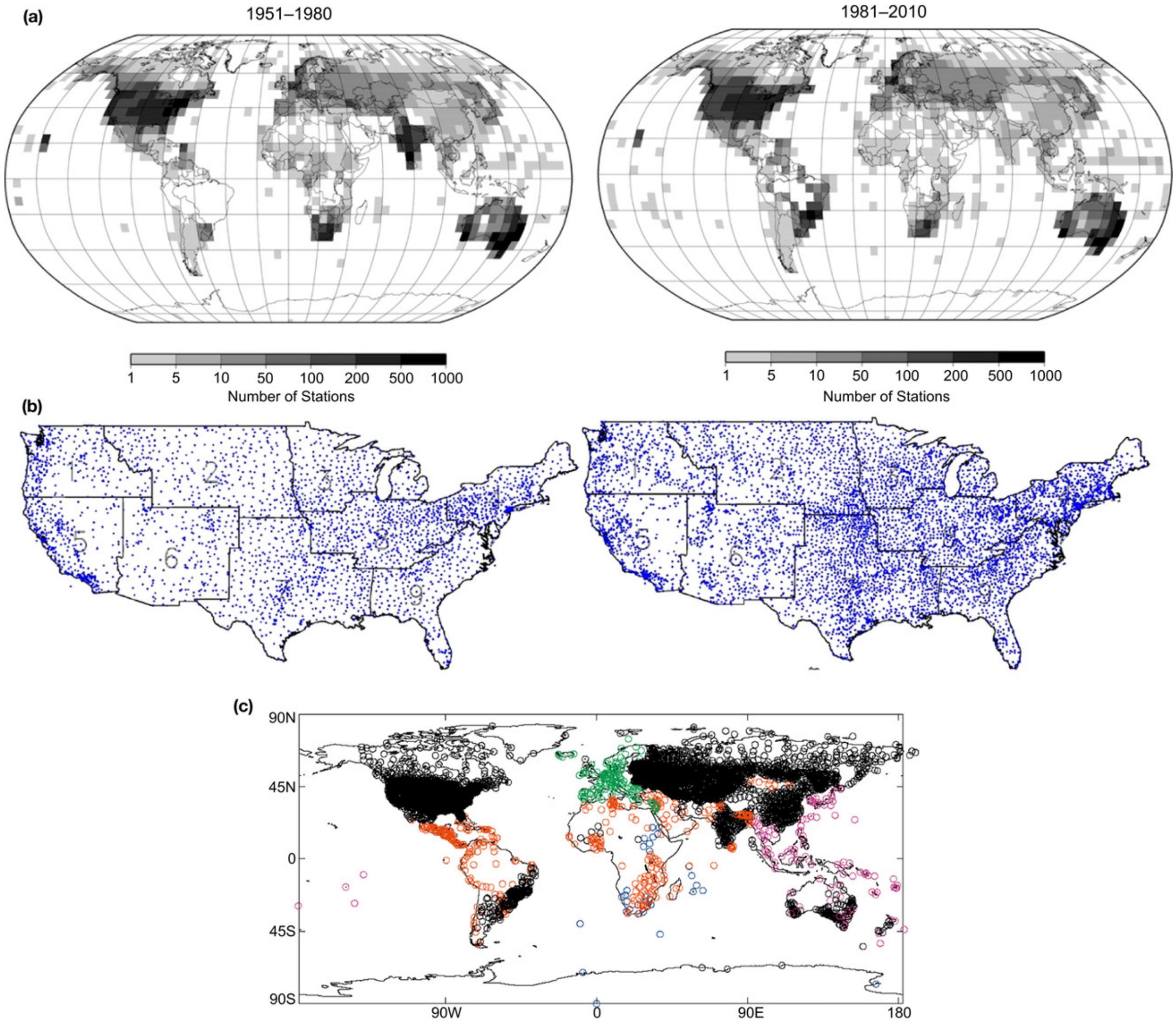

Figure 4 (a) Maps indicating the density of stations that have at least 10 years of precipitation records during the past successive 30-year intervals (source: http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/). (b) Two station networks with long-term precipitation time series of hourly and daily precipitation available for the past 60 years over the CONUS. Blue dots on the maps show distribution of 3076 HPD stations (left) and 5885 long-term daily COOP observer stations (right), adapted from Groisman et al. (2004, 2012). Boundaries of regions used for area-averaged climatologies and change analyses in these studies are also shown. (c) Stations used in the recent near-global assessment of changes in intense precipitation (Alexander et al. 2006). Colors in this map are used to show the stations with daily precipitation from different sources. The largest of these sources (black dots) is GHCN-daily. Total number of stations is 5948.

rainfall intensity. First, we present a few examples and then discuss their consequences.

- In the late 1930s, the Norwegian Meteorological Service began sending letters of appreciation to its observers. In response, they began working even more diligently and reported each 0.1 mm of precipitation in their daily reports. Fifty years later, Groisman et al. (1999) found a significant century-long increasing trend in the number of wet days over this nation that was completely explained by a jump in the number of rainy days with 0.1 mm that were practically absent in the past records.
- In 1966–67, the Hydrometeorological Services of the former Soviet Union and later of Finland made concise efforts to account for light precipitation ‘to the last drop’ and introduced wetting corrections to each nonzero precipitation measurement (0.2 mm for liquid and 0.1 mm for frozen precipitation; when at least one drop was extracted from the gauge it was assumed to be a 0.1 mm). The number of days with precipitation increased and the total reported precipitation increased by 5–10% and up to 30% in the Arctic regions (Shver 1976; Groisman and Rankova 2001).
- After Canada switched from British units to SI (for precipitation, the measure changed to mm instead of 0.01 inch), all statistics of rainfall and snowfall occurrence became ‘slightly’ incomparable. This and several changes in instrumentation (cf., Metcalfe et al. 1997; Mekis and Hogg 1999) made it very difficult to assess changes in the light

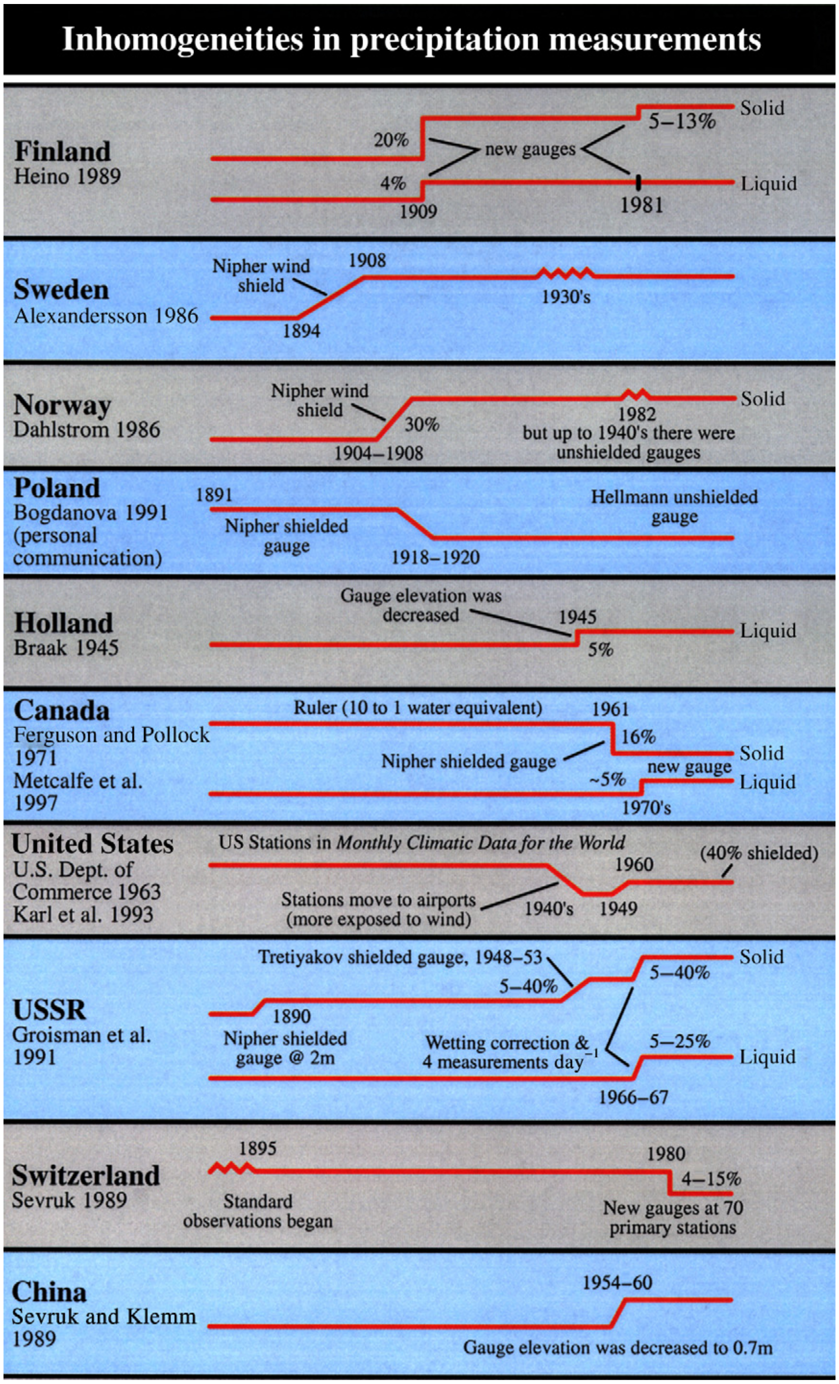
Inhomogeneities in precipitation measurements
Finland
Heino 1989
20%
4%
new gauges
5–13%
Solid
Liquid
1909
1981
Sweden
Alexandersson 1986
Nipher wind shield
1908
1894
1930's
Norway
Dahlstrom 1986
Nipher wind shield
30%
1904–1908
1982
but up to 1940's there were unshielded gauges
Solid
Poland
Bogdanova 1991 (personal communication)
1891
Nipher shielded gauge
1918–1920
Hellmann unshielded gauge
Holland
Braak 1945
Gauge elevation was decreased
1945
5%
Liquid
Canada
Ferguson and Pollock 1971
Metcalfe et al. 1997
Ruler (10 to 1 water equivalent)
1961
16%
Nipher shielded gauge
~5%
new gauge
Solid
Liquid
1970's
United States
U.S. Dept. of Commerce 1963
Karl et al. 1993
US Stations in Monthly Climatic Data for the World
1960
(40% shielded)
Stations move to airports (more exposed to wind)
1940's
1949
USSR
Groisman et al. 1991
Tretiyakov shielded gauge, 1948–53
5–40%
5–40%
Solid
1890
Nipher shielded gauge @ 2m
Wetting correction & 4 measurements day⁻¹
5–25%
Liquid
1966–67
Switzerland
Sevruk 1989
1895
Standard observations began
1980
4–15%
New gauges at 70 primary stations
China
Sevruk and Klemm 1989
1954–60
Gauge elevation was decreased to 0.7m

Figure 5 Major instrument and/or methodology changes at the national precipitation network of several countries of the Northern Hemisphere and average order of biases (inhomogeneities) caused by these changes (Karl, T. R., R. G. Quayle, and P. Ya. Groisman, 1993: Detecting climate variations and change: new challenges for observing and data management systems. *J. Clim.*, **6**, 1481–1494.).

precipitation occurrence over this nation (let us recall that even in southern Canada the median daily precipitation total is on the order of 1 mm).

Figure 6 illustrates the inhomogeneity of information stored in the US and Canadian digital archives regarding the low intensity precipitation. For example, in the United States, the number of 0.01 inch precipitation reports steadily grew from 6 to 13 year^{-1}. Reports of 0.02 and 0.03 inch daily precipitation remained steady since the 1940s but prior to these years they were also less frequently reported. During the 1961–90 period, on average, there were 88 days with nonzero precipitation nationwide and ~19 of them (22%) reported from 0.01 to 0.03 inches of precipitation. In the beginning of the twentieth century, these numbers were close to 11 days and 100 years later exceeded the 20 days threshold, i.e., nearly doubled. In the

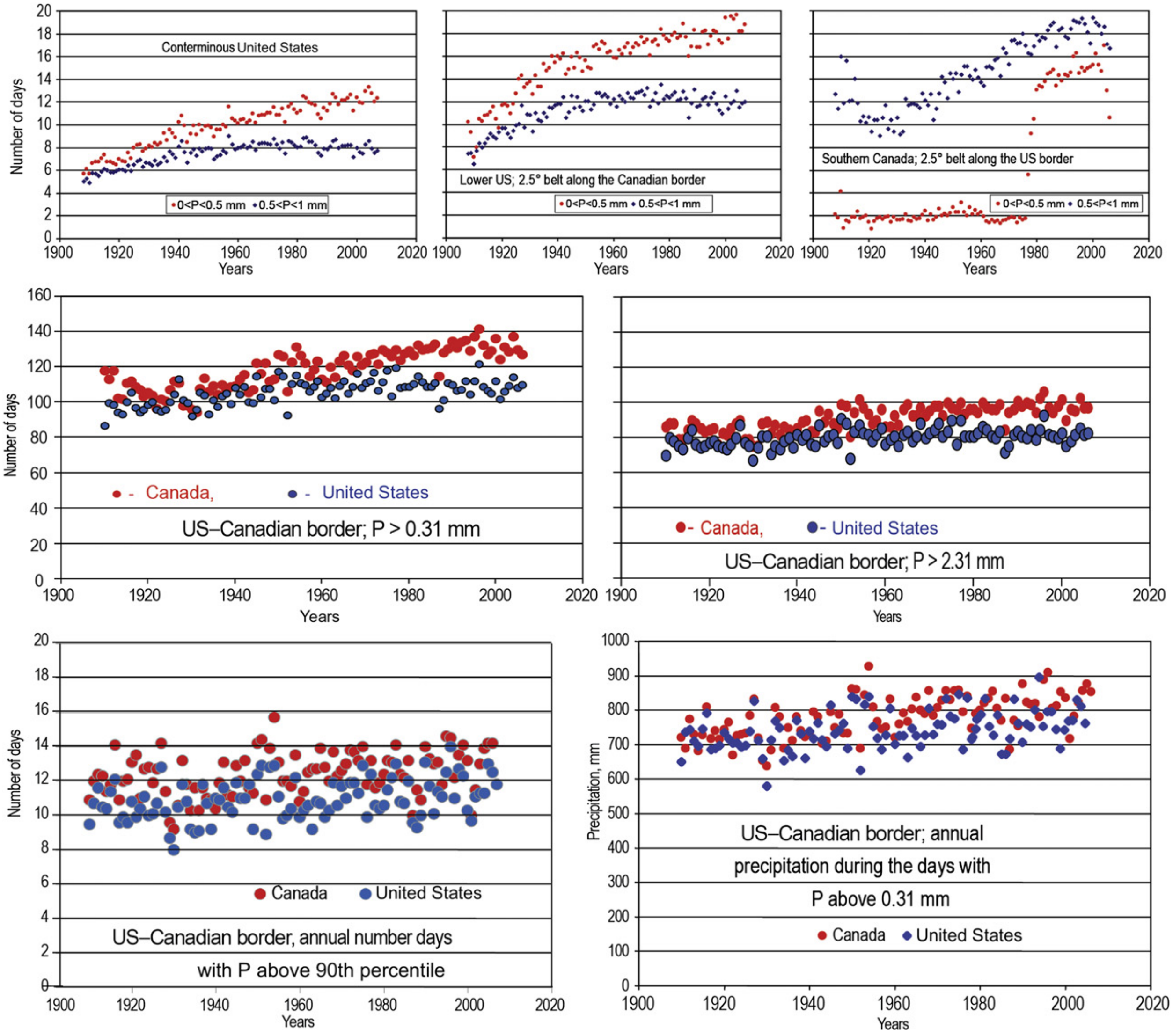

Figure 6 (Top panel) Mean number of days with nonzero very light daily precipitation over the conterminous United States (left; Groisman and Knight 2007, 2008) and along the 2.5° latitudinal belt along the US–Canadian border, US (center) and Canadian (right) sides of the border. (Middle panels) Annual number of days across the US–Canadian border (±2.5°lat.) with precipitation (left) above 0.31 mm and (right) above 2.31 mm. Blue and red dots show the US and Canadian precipitation frequency, respectively. Note the difference in trends, first of all, for Canada. (Bottom panels) Annual number of days across the US–Canadian border (±2.5°lat.) with heavy precipitation (upper 10th percentile; left) and precipitation totals for days with P above 0.31 mm (right). Blue and red dots show the US and Canadian precipitation frequency, respectively. Due to station network paucity, only the border between the conterminous U.S. and southern Canada are assessed in all graphs of this Figure.

northern United States along the Canadian border the effect is even more pronounced. During the 1961–90 period, on average, there were 118 days with nonzero precipitation and ~30 of them (25%) reported from 0.01 to 0.03 inches of precipitation. Since the beginning of the twentieth century, the number of reported 0.01-inchers nearly doubled and the number of reported 0.02- and 0.03-inchers increased from ~8 to ~12 in the 1940s and remained steady thereafter.

We actually expected this problem only on the Canadian side of the border (cf., Vincent and Mekis 2006). These authors reported very large trends in the number of days with precipitation entirely across Canada treating them as a true finding. We hypothesized that this is a result of the changing of instrumentation and observing practices in Canada (Groisman et al. 2003). Figure 6 (top panel) supports this, our claim, and illustrates the inhomogeneity of information stored in the Canadian digital archives for the southernmost part of the country along the US border. Here, the number of daily precipitation reports of less than 0.5 mm increased from 2 to 14 year^{-1} after the introduction of metric (instead of British) units and rain gauges with a transparent bucket. The number of reports of daily precipitation in the interval within 0.5–1.0 mm interval in this part of Canada has also changed during the past 100 years by 90% from ~10 to ~19 year^{-1}.

After encountering the problem with low intensity precipitation reporting, it is worthwhile to sacrifice the low precipitation daily bins (in any case, they were not consistently reported during the past century) and to find the thresholds (cutoff breakpoints) after which we can reliably analyze time series of 'days with sizable precipitation' (i.e., days with precipitation above these thresholds) as well as precipitation totals over southern Canada. Various cutoff breakpoints were used to eliminate a range of smaller values from the analyses of 'days with precipitation.' Below, we show an empirical approach to assure that there is a possibility to assess the 'sizeable' precipitation trends even in the presence of the inhomogeneities reported in Figure 6.

We discarded the day with precipitation below 0.01″ (using cutoff value 0.31 mm), and compared the trends across the border. Then, we incremented the cutoff value by another 0.01″, etc., up to days with precipitation below 0.1″ (or 2.6 mm) from both sides of the border and compared trends for the past century. We did not see problems with the US trends (very soon they became invariant to the breakpoint selection). But, for southern Canada, in order to extract what appear to be reasonable trends (i.e., similar to those observed in a close southward proximity), it was found that only the value 2.31 mm (which eliminates 0.09″ and lower daily precipitation events) is a safe value along the entire border (Figure 6, middle panels). Further testing indicates that it is possible to use smaller cutoff points for days with precipitation, if we are intending to analyze the data only after 1978–80 (the years when most of the changes causing homogeneity problems last occurred in the Canadian observation practice). Similar analyses performed for total precipitation and for days with heavy (upper 10th percentile) and very heavy (upper first percentile, not shown) precipitation show that the 'breakpoint' problem is not acute and does not create changes between the slopes of trends across the US–Canadian border (Figure 6, bottom panels).

Any analysis of temporal changes in the HPD data has to account for one important change at the network since 1960s: From 1948 to 1960, all of the gauges recorded with a resolution of 0.254 mm (0.01 inch). These gauges were gradually replaced so that currently more than 85% of HPD gauges record to a resolution of 2.54 mm. Fortunately, this gradual replacement of gauges is well documented and it is possible to homogenize the time series (cf., Groisman et al. 2012) for the entire period of record. This conversion is of critical importance. Without this adjustment for gauge resolution, an unaware user could generate grossly false conclusions about the changes in precipitation duration and intensity. The accuracy of the COOP network rain gauges has remained 0.254 mm throughout the entire period of observations.

All of the above have one problem in common: instability of reporting of light precipitation (in the daily and hourly totals). The researchers who intend to assess the upper tail of the precipitation distribution using upper percentiles, can be hurt from the low end of this distribution because

- estimates of the number of observed no-rain days and estimates of 'daily intensity' (precipitation totals divided by the number of days with precipitation) can be contaminated by artificial trends;
- on the hourly time scale, estimates of the rainfall duration and intensity trends can be extraordinarily high (and opposite in sign) if the resolution of the gauges changes with time;
- the attempts to estimate the daily precipitation distribution (e.g., with gamma-distribution) and its changes with time can be affected by the changing numbers of low values that are close to zero (which, over most of extratropics, are the most frequent precipitation events); the following assessment of the upper tail of this distribution and its changes will be in trouble; and finally,
- the upper percentiles of daily precipitation each year can be based on a very different fraction of rain days (cf., Figure 6).

Different ways to handle this problem can be found in Groisman et al. 1999, 2012; Rosenberg et al. 2010; and Mishra et al. 2012.

The last (less frequent) data problem that may affect researchers who study heavy precipitation is a changing amount of the accumulated daily precipitation totals with time. So far, we found only one country (Australia, cf., Groisman et al. 1999) where this problem is sufficiently severe and had to be resolved prior to further analyses of heavy precipitation changes. When the post offices in this country switched from a 6- to 5-day work week schedule, a substantial part of the national precipitation network located at these offices began reporting Monday extreme rainfall and the previous days were missing.

5.03.2.3 Geographical Distribution of Changes in Intense Precipitation

Approximately 15 years ago, studies of global-wide changes of intense precipitation were virtually absent because the appropriate data sets did not exist (i.e., long-term time series with daily and/or hourly resolution from dense international networks of meteorological stations). National data sets existed but they were not shared simply because there appeared to be little interest in working with them. The situation gradually changed after first reports about potentially dangerous tendencies of increasing of intense rainfall in the upper percentiles of its daily distribution (Iwashima and Yamatomo 1993; Karl and Knight 1998) and theoretical expectations of further development of these tendencies in the warmer climate were projected with human-induced changes in the atmospheric composition (Meehl et al. 2007).

Initially, the number of stations used in these analyses was quite modest. For example, the first daily station data set employed by Karl and Knight (1998) included the long-term daily precipitation time series of only 182 stations over the CONUS (compared to more than 6000 stations used in the present national analyses such as USCCSP 2009). This paucity of stations, in turn, allowed analyses of intense precipitation only above the upper fifth percentile or annual/monthly maximum rainfall that (a) did not qualify to be truly extreme events and (b) in the case of annual maximum, can be misleading in the regions where precipitation changed at both ends of its distribution (cf., *Cautious Note* in Section 5.03.1.2.2). It became clear that without preparation of expansive international precipitation data sets with daily time resolution, no further advance would be possible. First efforts to compile such data sets were made at the US National Center for Atmospheric Research (Spangler and Jenne 1984; Liebmann et al. 1999,

2001) and the NOAA National Climatic Data Center (NCDC; cf., http://www.ncdc.noaa.gov/oa/gsod.html; http://www.ncdc.noaa.gov/oa/climate/ghcn-daily/). These efforts were supported by the World Meteorological Organization with organizing regional workshops devoted to analyses of regional daily data. During the 1998–2008 period, 16 such workshops were organized (Peterson and Manton 2008) and their results were later reworked into scientific papers (cf., Peterson et al. 2002; Easterling et al. 2003; Aguilar et al. 2005, 2009; Sensoy et al. 2007; etc.). Furthermore, NCDC invited scientists from different countries who have expertise (and access to scientific quality national data sets) to visit the Center for joint data quality analyses (e.g., Groisman and Rankova 2001; Ren et al. 2005) and joint assessments of changes in heavy precipitation (Groisman et al. 1999, 2005; Easterling et al. 2000; Groisman et al. 2005; Alexander et al. 2006). Gradually, from these studies a mosaic of systematic changes in intense precipitation over the globe was compiled and revealed several systematic features of changes in intense and heavy precipitation (Figure 7).

- Over most of the extratropics in the rainy season with the highest rainfall, intense precipitation (rain events in the highest upper percentiles of daily distribution) became more frequent during the past 50–60 years.
- In the tropical zone, the sign of changes varies; there are regions where heavy precipitation frequencies increased and other regions where they decreased.
- If there was a significant increase in mean seasonal precipitation, the increase in the upper percentiles (heavy precipitation) was disproportionally large compared to changes in mean precipitation.
- In several large regions (e.g., northern Asia, Mediterranean, central Mexico) where the mean precipitation did not change or even decreased, the heavy precipitation events nevertheless became more frequent.

Figure 7 is a third generation of the picture first presented in Easterling et al. (2000) and thereafter in Groisman et al. (2005), where signs (+ and −) show the regions with observed changes in heavy precipitation that follow the pattern outlined above: changes in mean precipitation are less or insignificant, while changes in heavy/very heavy precipitation are statistically significant. Initially, the shading on the map indicated the countries for which the authors' team had and analyzed the data themselves, but gradually the distinction became only historical because other scientists have studied most of these regions as well and reached similar conclusions. While there were efforts to unify the definitions used to characterize intense (heavy, extreme) precipitation over the globe (cf., Frich et al. 2002), they cannot be considered successful. Different research agendas faced by the scientists in different countries and different disciplines (civil engineers, hydrologists, climatologists, and agriculturists), and the different amounts of data they had to address these agendas actually dictated the selection of thresholds used for definitions of terminology of intense precipitation categories (cf., discussion in Section 5.03.1.2 Definitions of Intense Precipitation). Therefore, the regional results that we shall describe below are diverse and thus require individual description.

Moreover, according to our classification in Table 1, most of these results are devoted to changes in the frequency of heavy and very heavy precipitation events but not of extreme events (although the authors frequently name them 'extremes,' e.g., the upper 5% of daily rainfall distribution or the annual maximum rainfall). We again have to warn about the use of 'dynamic' definitions when, for each year, the high end of daily rainfall distribution is selected to characterize very heavy and/or extreme rain events. In dry years, these events may be 'not at all heavy or extreme,' and in some regions may hide the actual changes at the high end of the daily rainfall distribution (cf., *Cautious note* in Section 5.03.1.2.2 Cautious Note).

5.03.2.4 Updated Analyses for Several Large Regions of the Northern Extratropics

Below, we decipher signs presented in Figure 7 as they were first presented in Groisman et al. (2005), updating and/or supporting them with results of other studies.

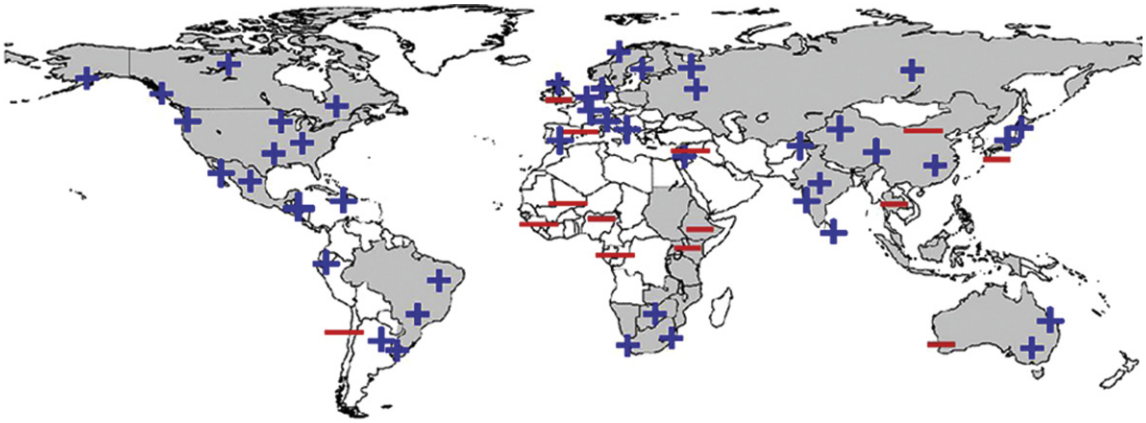

Figure 7 Regions where disproportionate changes in heavy and very heavy precipitation during the past decades were documented compared to the change in the annual and/or seasonal precipitation (Easterling et al. 2000; Groisman et al. 2005; substantially updated first in Trenberth et al. 2007 and for the present chapter). Thresholds used to define heavy and very heavy precipitation vary by season and region. However, changes in heavy precipitation frequencies are always higher than changes in precipitation totals, and, in some regions, an increase in heavy and/or very heavy precipitation occurred while no change or even a decrease in precipitation totals was observed.

5.03.2.4.1 European Part of the Russian Federation

In the European part of the former USSR, more than 700 long-term stations during the period 1936–97 were available to Groisman et al. (2005) for analyses of 'heavy,' 'very heavy,' and extreme precipitation defined as upper 5–10% (heavy), 1–0.3% (very heavy), and 0.1% (extreme), respectively. Most of the newly independent states of this territory (except Russia and Belarus) do not share sufficient volume of their meteorological observations with international archives. Therefore, now for similar analysis during the period 1936–2010 in the European part of the Russian Federation, we can use the data of 335 long-term Russian stations. In general, maximum precipitation in this area occurs during the warm season, with very heavy rainfall coming almost entirely from convective clouds (Sun et al. 2001). Note that approximately 95% of the daily precipitation events are still less than 10 mm day^{-1}. **Table 2** presents the results of trend analyses for these two regions for the summer season. Both show a large increase of about 10% in summer precipitation in the region for the study period although the century-long increase is smaller (e.g., Groisman and Rankova 2001). During the same period, the rate of increase in heavy precipitation, in very heavy precipitation and in extreme rainfall, was higher than for mean summer precipitation (for the summer season, we use here a 0.3 percentile as a threshold to define extreme rain events that occur in these two regions approximately once in 10 years). The linear trend of the time series of heavy precipitation was statistically significant at the 0.01 level in both regions. In the southern region, trends in very heavy (upper 1% of rain events) and even in extreme *annual* precipitation are also statistically significant at the 0.05 level or above for the former USSR during the period 1936–97. For the extended period 1936–2010, the sign and absolute values of trends in very heavy and extreme *summer* precipitation became statistically insignificant. An updated precipitation time series for this region shows a continuation of the precipitation increase as well as the increase of the frequency of intense rain events of various strengths up to 2009. The rates of change did not appreciably change compared to the annual events for the shorter period, but the thresholds and the level of interannual variability of the area-averaged number of days with heavy and extreme summer rainfall are higher than those for precipitation during the entire year. Moreover, in 2010, a dramatic summer drought (cf., Mescherskaya et al. 2011; Barriopedro et al. 2011) contributed to this variability. It did not reverse the trends in the frequency of heavy, very heavy, and extreme rain events in this part of the world but zero values as the last points of time series of very heavy and extreme rain event counts did not add to trend estimates either.

5.03.2.4.2 Fennoscandia

Fennoscandia is very well covered by precipitation stations (**Figure 4**), but only a fraction of the daily data for this network is publicly available (Klein Tank et al. 2002), or for special research projects such as Arctic Climate Impact Assessment (ACIA 2005). There were previous reports describing the total precipitation increase in northern Europe (Hanssen-Bauer et al. 1997; Heino et al. 1999; Førland and Hanssen-Bauer, 2000; Folland and Karl 2001), but they all reported a smaller relative change compared to Groisman et al. (2005) for changes in 'very heavy' precipitation frequency defined as the upper 0.3% of daily precipitation events both in summer (a season with the most intense precipitation) and throughout the year (**Figure 8**). All increases have occurred since the 1980s. The average regional upper 0.3% thresholds are 50 and 45 mm for summer and annual, respectively.

A 66% increase to the early 2010s of the summer frequency of very heavy daily rain events (a region-wide average of 50 mm, but along the Norwegian Sea Coast it was much higher), which in the early 1950s approximately occurred once per decade, became a large problem because it coincided with changes in an intra-season distribution of the rainy days. Recently for Norway, Zolina et al. (2012), after analysis of the daily data of more than 200 national stations, showed a simultaneous shortening of wet periods for the past 60 years in southern Norway along the Sea Coast in the warm season, and a significant increase in the cold season. This implies that while the winter precipitation can

Table 2 Trend characteristics of the summer precipitation for the western part of the Russian Federation over the period 1936–2010. Mean totals and the number of days with precipitation above upper percentile thresholds. Trend values statistically significant at the 0.05 level or at the 0.01 level are marked with asterisks (*) and double asterisks (**), respectively (updated archive of Groisman et al. 2005).

				Number of days with $P >$ Thr. Linear trend and its variance	
Precipitation		*Mean values*	*Thresholds (Thr.), mm*	*% 50 year^{-1}*	*%*
North of European Russia (north of 60°N)					
Total, mm		190	0.5	12	9**
Heavy, days	90th percentile	3.4	7	17	9**
	95th percentile	1.7	11	24	11**
Very heavy	99th percentile	0.36	23	13	1
Extreme	99.7th percentile	0.12	33	–	0
European part of the Russian Federation south of 60°N					
Total, mm		180	0.5	9	6**
Heavy, days	90th percentile	2.8	6	14	10**
	95th percentile	1.4	11	19	9**
Very heavy	99th percentile	0.29	25	14	3
Extreme	99.7th percentile	0.10	38	18	3

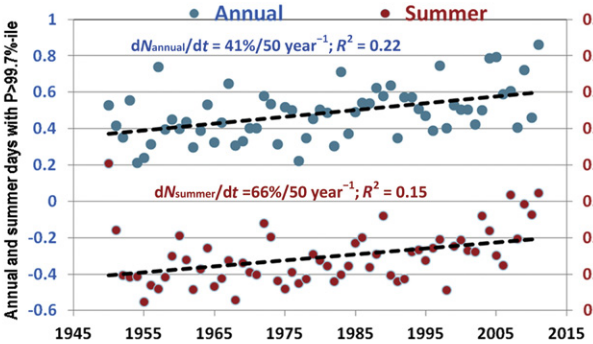

Figure 8 Frequency of very heavy (above the upper 0.3 percentile) annual (blue) and summer (dark red) daily precipitation events during the 1950–2011 period over Fennoscandia. All linear trends (shown by dashed lines) are statistically significant at the 0.01 level or above (updated time series from Groisman et al. 2005). Mean regional numbers were produced by the arithmetic averaging of the actual stations' numbers of days with very heavy precipitation within the 1 × 1 grid cells with the appropriate area-weights averaging of the grid cell values.

be more equally spread within the larger wet spells, in summer, intensity of daily rainfall should disproportionally rise (as predicted by Groisman et al. 1999) and is shown in Figure 8. It is worthwhile to note that the summer precipitation totals area-averaged over Fennoscandia did not change during the past 60 years. During the past 60 years, annual totals of *measured* precipitation over Fennoscandia have increased with a mean rate of 30 mm per decade. Part of these increases is real, but a sizeable fraction of increase is due to a better snowfall catch of the new Finnish gauges (Figure 5) and a general shift in the ratio between liquid and frozen forms of precipitation with regional warming (all contemporary rain gauges catch a larger fraction of rainfall than of snowfall; cf., Førland and Hanssen-Bauer 2000; Goodison et al. 1998).

5.03.2.4.3 Canada

Stone et al. (2000), while analyzing heavy precipitation over Canada, had to account for restrictions imposed by frequent low intensity precipitation over most of the nation with respect to the definition of heavy precipitation. They argue that when the upper decile of daily precipitation events can correspond to a threshold of ∼0.5 mm, it is difficult to consider these events 'heavy' (e.g., in northern Canada). Furthermore, our analysis (cf., Figure 6) shows that the analysis of frequent light precipitation events in Canada is challenging, but when looking for precipitation above 5 mm day^{-1} the process is trouble-free entirely across Canada. Fortunately, Stone et al. (2000), in their definition of heavy precipitation, used this value as a minimum threshold ($T_5 = 5\ \text{mm day}^{-1}\ (1 + n)$, where $n = 0, 1, 2$, etc.; the n-values were individually selected at each station in order to secure at least five events per year in each 3-month-long season of the 1960–90 reference period). Such sophisticated selection allowed them to analyze the changes of sizeable precipitation events at the upper end of the daily distribution across the entire nation that (a) are all above 5 mm and (b) consider on average approximately 20 precipitation events per year as heavy events. The authors grouped their stations into five large regions with similar patterns of precipitation changes (southeast, northeast, Arctic Canada, southwest, and northwest). The frequency of thus defined heavy precipitation events during the analyzed period of 1950–95 increased over the densest populated part of Canada, the *southeast*, in the spring–summer season (April through August). This region is relatively humid (thus, the selected n-values there were among the highest in the nation). Over *northeastern Canada* they reported an increase in heavy precipitation in the spring months and in the last 5 months of the year. Over *Arctic Canada*, heavy events frequency increased significantly during most of the year (except the summer months). Over *northwestern Canada*, heavy precipitation events increased in winter and spring, while no changes in heavy precipitation were documented in *southwestern Canada* in any 3-month-long part of the annual cycle. It is notable that no large region across the nation was found to have a 3-month-interval where statistically significant decreases in heavy precipitation were documented during the 1950–95 period (Stone et al. 2000).

5.03.2.4.4 Pacific Coast of Northwestern North America

The Pacific coast of northwestern North America is the only large high latitude region with both large annual precipitation totals and a sufficiently dense precipitation network available for our analyses in the Western Hemisphere. The mountainous character of these two regions makes the heavy precipitation here an important issue because of the landslide and flash flood danger. Figure 9 shows the time series of the frequency of heavy and very heavy precipitation in southern Alaska (south of 62°N) and British Columbia, Canada (BC; south of 55°N). These time series were first presented by Groisman et al. (2005) and here they are updated to 2010. In both regions, precipitation increased during the period of record, but the double-digit increases in the frequency of heavy and very heavy precipitation are especially noteworthy (Table 3). Given the high thresholds for these events, these changes reflect an increasing societal and/or environmental threat in both areas. Note that in southern Alaska in the last 8 years, the frequency of very heavy precipitation returned to long-term mean values and the trend of their occurrence is statistically insignificant.

5.03.2.4.5 Mexico

Analyzing variability of the heavy daily precipitation occurrence (upper 10 and 5% of daily rain events mostly in the winter season) in northern Baja California during the 1950–2000 period, Cavazos and Rivas (2004) linked this occurrence to the strong impact of El Niño events and neutral ENSO conditions in the region. While linking most of the variability to ENSO and tropical moisture transport into the region associated with El Niño 'pineapple express,' they also documented a shift of heavy precipitation distribution, with a relatively dry period and less variability during 1950–76, followed by a relatively wet period and more variability during 1976–2000. Variability in this dry region means more frequent heavy rain events, some of which caused flooding and losses of life in the city of Tijuana. Southward, over the central Mexican Plateau, the changes in summer heavy

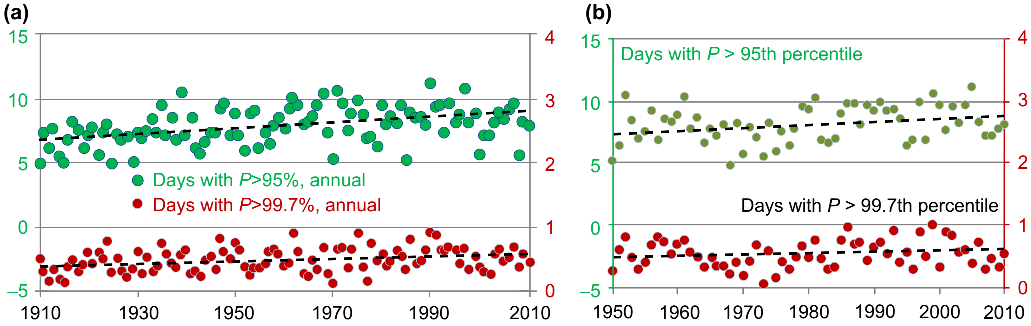

Figure 9 Heavy and very heavy annual precipitation variations and linear trends along the northwestern coast of North America (a) British Columbia south of 55°N and (b) Alaska south of 62°N. Statistical significance of linear trends is provided in **Table 3**. Mean regional numbers were produced by the arithmetic averaging of the actual stations' numbers of days with heavy and very heavy precipitation within the 1 × 1 grid cells with the appropriate area-weights averaging of the grid cell values.

Table 3 Heavy and very heavy annual precipitation along the northwestern coast of North America. Values of mean annual precipitation, area-averaged thresholds for heavy (upper fifth percentile) and very heavy (upper 0.3 percentile) are shown. Trend estimates in total precipitation and annual number of days above the two thresholds are also presented. Trend values statistically significant at the 0.05 level or at the 0.01 level are marked with asterisks (*) and double asterisks (**), respectively.

	Total precipitation		*95th percentile threshold*		*99.7th percentile threshold*	
Region, Period assessed	*Mean mm*	*Trend % 50 year^{-1}*	*Value mm*	*Trend % 50 year^{-1}*	*Value mm*	*Trend % 50 year^{-1}*
British Columbia, south of 55° N 1910–2010	1625	6.1**	26	12**	56	16**
Alaska, south of 62° N 1950–2010	1635	6.8*	28	13*	66	17

precipitation (the upper 5% of daily rain events or those above the 25–35 mm thresholds) followed the change of the mean precipitation that was decreasing in the last three decades prior to year 2005 (Groisman et al. 2005). However, the frequency of very heavy precipitation (above the upper 1 and 0.3% of the rain events or above 55 and 75 mm, respectively) increased during the same 30-year-long period. The frequency of very heavy rain events (above the upper 0.3%) has substantially increased (by 110% per 30 years). Thus, while in the early 1970s, the average return period of such events was approximately 12 years; in the early 2000s it is estimated to be around 5 years.

5.03.2.4.6 Contiguous United States

Studies of the changes in heavy and very heavy precipitation over the CONUS (cf., Karl and Knight 1998; Groisman et al. 2001, 2004, 2005; Kunkel et al. 1999, 2003, 2007) were summarized in USCCSP (2009) and Karl et al. (2009). In these National Assessments it was shown that over the entire eastern two-thirds of the CONUS, daily and multiday precipitation events became more frequent and the most prominent increases occurred over the northeastern quadrant of the CONUS (Figure 10).

In the southeastern United States very heavy and extreme precipitation associated with tropical storms and hurricanes has increased (Knight and Davis 2009; Kunkel et al. 2010; Wang et al. 2010), while other intense rainfall occurred less frequently in the past decades (archive of Groisman et al. 2012; Figure 2). This development allowed Wang et al. (2010) to conclude that during the 1948–2007 period, the southeast summer rainfall exhibited higher interannual variability with more intense summer droughts and anomalous wetness in the second 30 years (1978–2007) than in the prior 30 years (1948–77).

For the eastern regions of the CONUS, the recent elevated numbers are the largest since reliable records began in 1895. For western regions, the recent decades are comparable to the early part of the historical record.

For the past three decades, *in the central United States*, Groisman et al. (2012) reported a considerable increase in very heavy and extreme rainfall (up to 40% increase for daily and multidaily events above 155 mm or 6 inches; Figure 11). However (after checking all other possible causes in addition to the ongoing global warming), they hypothesized that at least a part of this tremendous rise in extreme rainfall might be associated with local anthropogenic forcing, intensification of land use, and doubling and/or quadrupling of corn and soybeans yield in the area.

In addition to the frequency changes of intense precipitation, its intensity has increased over the entire CONUS. Figure 12 (top) shows nationwide changes in intense precipitation that comes in fixed 1- and 2-day-long strings of consecutive rain days (defined here as a day with daily total above 12.7 mm or 0.5 inch). Together, 1- and 2-day-long strings represent 97.5% of all intense rainfall days and deliver 93% of its precipitation. Over the Midwest, the rainfall that comes in 3- and 4-day-long consecutive days has also significantly increased (Figure 12, bottom). In this part of the United States, frequency of the 4-day-long consecutive rainfall events (that comprise *on*

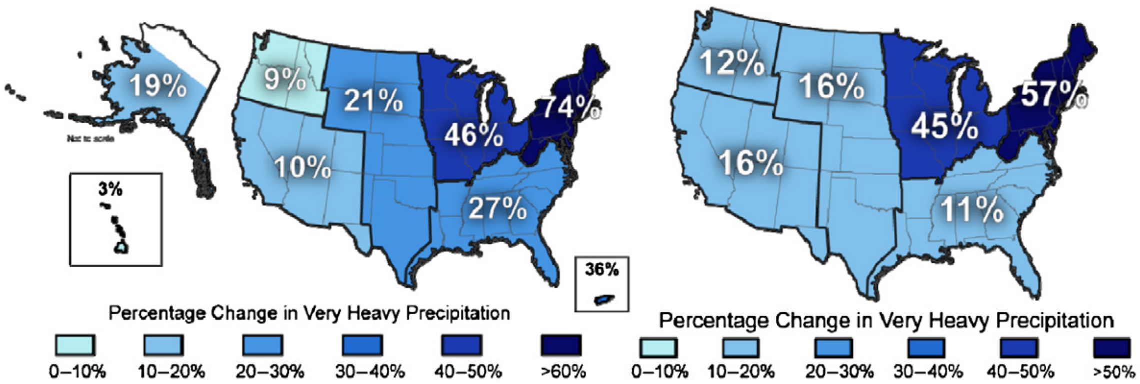

Figure 10 Observed increases in very heavy precipitation during the 1958–2010/11 (update of similar finding presented in Karl et al. 2009). (Left) Percent increases in the annual amount falling in very heavy rain events defined as the heaviest 1% of all daily events from 1958 to 2010 for each region of the United States. Changes in the eastern half of the nation are statistically significant at the 0.05 or higher levels and over the Great Plains, at the 0.1 level. (Right) Percent increases in the amount falling in very heavy rain events defined as the heaviest 1% of all daily events from 1958 to 2011 in the summer season for each region of the CONUS. Changes over the north-central and north-eastern parts of the nation are statistically significant at the 0.01 and 0.05 levels, respectively; all other trends are insignificant.

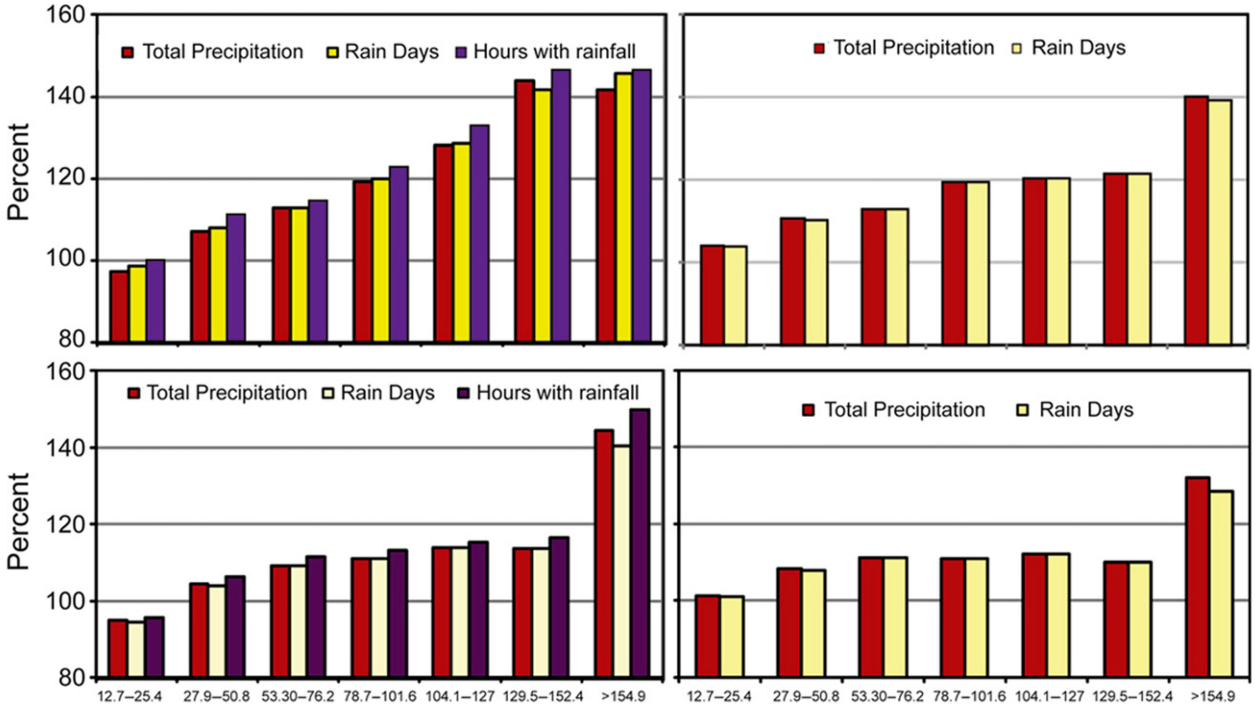

Figure 11 Comparison of intense precipitation days (upper line of plots) and multiday intense precipitation events (lower plots) over the central United States for 1979–2009 and 1948–78 periods sorted by day/event intensities (in mm). Estimates of precipitation characteristics for these 31-year periods were averaged and their ratios (in percent per station) are shown for HPD (left) and COOP (right) networks. Groisman, P. Ya., R. W. Knight, and T. R. Karl, 2012: Changes in intense precipitation over the central U.S. *J. Hydrometeorol.*, **13**, 47–66. [Available online at http://dx.doi.org/10.1175/JHM-D-11-039.1]

average 5 inches of rain) has been increasing in the past decades.

5.03.2.5 An Independent Near-Global Assessment of Changes in Intense Precipitation

Povl Frich (1999) developed a suite of indices that were proposed to be used as characteristics of climatic change. The pioneering idea beyond this proposal was a comprehensive suite of daily characteristics of temperature and precipitation that (together with the mean characteristics of climate) includes characteristics that can be used to describe anomalously high (low) climate conditions (extremes) and their changes. Among these characteristics were variables that are well suited to describe changes in intense precipitation. These characteristics do not describe 'extreme' rainfall as a very rare event (cf., as defined in Table 1) but instead these precipitation indices are flexible, easy to calculate, and their suite (with some reasonable modifications) can be used to describe heavy and very heavy

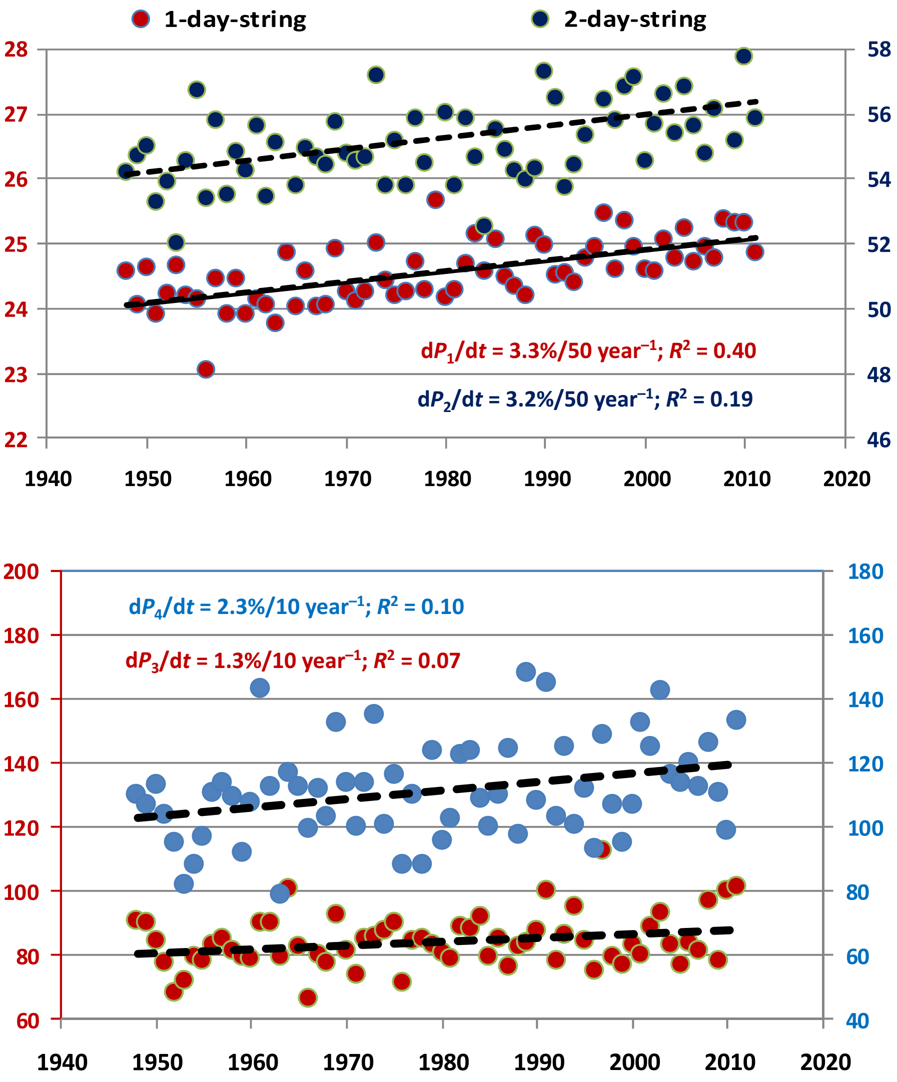

Figure 12 (Top panel) Mean intense precipitation, mm, per event that comes with 1- and 2-day-long events over the CONUS. The estimates are based on all intense events above 12.7 mm at ~6000 long-term US cooperative stations for the 1948–2011 period (Archive of Groisman et al. 2012). (Bottom panel) The same but for 3- and 4-day-long events over the midwestern United States.

precipitation across the world. These indices include the number of days with precipitation above 10 and 20 mm, annual daily maximum rainfall, maximum annual 5-day rainfall total, upper 95th and 99th percentile rainfall totals, and counts of daily events. These indices have been broadly used in regional and international assessments of intense precipitation change (cf., Frich et al. 2002; Alexander et al. 2006; You et al. 2008; Caesar et al. 2011; Easterling et al. 2003; Peterson et al. 2002; Aguillar et al. 2005, 2009; etc.). Below, we shall name them Frich indices. Frich indices were used in near-global and continental assessments of changes in the climate 'extremes' (cf., Frich et al. 2002; Klein Tank and Können 2003; Easterling et al. 2003; Moberg et al. 2006; Haylock et al. 2006; Alexander et al. 2006). The most comprehensive among these near-global assessments (Alexander et al. 2006; cf. Figure 4(c)) is described below.

For the 1951–2003 period, Alexander et al. (2006) reported near-global increase in the number of days with precipitation above 10 mm and in the contribution of the upper 5% of rain events to the annual totals. The pattern of the regions with increases in intense annual precipitation includes most of North America, regions surrounding (and including) the La Plata River Basin and Southern Brazil, most of Europe, and large areas in southern and eastern Asia. Analysis of the seasonal changes in the maximum 5-day precipitation totals (RX5day) shows a quite similar pattern as two other annual indices except the June, July, and August (JJA) season when the areas with decrease in RX5day became more spacious and include, for example, Western Europe, extratropical Far East, most of Australia, and Southern Africa.

For the 1901–2003 period, Alexander et al. (2006) repeated their trend analyses over a smaller part of the land (CONUS, southern Canada, Europe, Russia, and Australia) and found an overwhelming tendency of increase in annual characteristics of intense precipitation at the long-term stations in these regions. This coherent signal over most of the extratropics (if true) is spectacular but it also raises some concerns (cf., Figures 5 and 6) because (a) national practices in all of these countries 'improved' their precipitation networks many times during the past century in order to provide better measurements (which means more rain is reported by gauges); (b) the redistribution between frozen and liquid precipitation has been shifted with global warming, which also resulted in a better gauge catch (cf., Førland and Hanssen-Bauer 2000); and (c) in Australia, the number of rainfall totals accumulated during the weekend significantly increased after the national post office, where many rain gauges reside, ended its Saturday service (Groisman et al. 1999). It should be determined if and how these instrumental inhomogeneities affected statistics of intense rainfall in the data sets used by Alexander et al. (2006). Common wisdom hints that (except for the Australian 'post office' factor and the regions with cold season maximum precipitation) the impact of instrumental inhomogeneities on changes of annual daily maximum rainfall should be miniscule.

Figure 7 generalizes the results for the regions that were not initially covered in Groisman et al. (2005), as well as provides updates and new findings for the regions that were initially assessed in that work. **Table 4** provides a summary of these findings (except those that have already been described above). In these studies, time intervals assessed are different and different characteristics of heavy precipitation were considered, but everywhere these were the estimates of changes in heavy and (in some cases) very heavy precipitation according to the definitions of **Table 1**. Data analyses that focus on extreme rain events and their changes in the CONUS are further presented in the next subsection.

5.03.2.6 Changes in Extreme Precipitation over the Contiguous United States

Practically all results presented in the previous two subsections of 5.03.2 (except those in **Figures 3 and 11**) describe regional changes in heavy and very heavy precipitation events (according to classifications presented in **Table 1**). Changes in extreme precipitation are considered in fewer studies and are concentrated in the areas with dense networks of long-term precipitation time series. The CONUS is one of these such regions. Three different types of analyses were conducted here to catch the changes in extreme precipitation. Each type is presented in a number of publications and research reports, and below we assess a few of them that are representative of these analyses.

NOAA Atlas 14. Efforts to update NOAA Atlas No. 2 that contains precipitation frequencies of different intensity and duration have been conducted during the past 10 years (new NOAA Atlas 14; Bonnin et al. 2004–2012). The approach of this study is as follows: All precipitation events at each NOAA meteorological station in the United States (there are more than 25 000 such stations and, thus, the work is very arduous) are documented, their duration, total, and mean intensity (e.g., hourly, 6-hourly, daily, 2-, 7-, …, 45-day totals, etc.) are defined and their frequencies are estimated during the period of record and separately for the past three decades to check the differences with the previous NOAA Atlas (No. 2). Among the most important practical tasks of the Atlas creators were calculations of exceedance values of rainfall for different return periods (1, 5, 10, 25, 50, 100, up to 1000 years). For large return periods for most of the stations (for return periods of 100 years and above, for all), these calculations cannot be done without some assumptions. Generally, there were two of them: (1) it was assumed that extreme value distributions (Gumbel 1954; Generalized Extreme Value, (GEV) (Coles, 2001) and Pareto (Hardy 2010)) can be employed to approximate the upper tails of precipitation distribution of different duration (accumulated totals), and (2) that some regional features (shape) of the upper tail precipitation distribution are similar (regions were selected using L-moments method, cf., Hosking 1990; Hosking and Wallis 2005). After comparison of the exeedance dynamics for 2- and 5-year return periods (i.e., for very heavy precipitation events), Bonnin et al. (2011) concluded that their results broadly coincide with findings of Groisman et al. (2004, 2005): trends in exceedances at 1-day and multiday durations were statistically significant and increasing for the Ohio River Basin and surrounding states. They also found that for the Semiarid Southwest there are no significant trends in extreme precipitation during the post-World War II period. For larger return periods (25 years and above), the authors concluded that their data-driven approach cannot deliver statistically significant trend estimates (confidence intervals of these estimates were ±30%, while the absolute values of trends were on the order of magnitude less).

Extreme precipitation in two more regions of the western United States. **Figures 3 and 11** have already shown results delivered by a direct approach used by Groisman et al. (2012) in order to investigate intense precipitation (including extreme rain events) over southeastern and central regions of the CONUS. They deliberately simplify the area-averaging by analyzing the multidecadal total frequencies at all stations available at that period omitting to account for possible clusters (in any case the assessment based on fixed thresholds does not allow for accurate regional representation of extreme precipitation events frequency) and carefully accounting only for the average number of stations available during these periods in order to receive the accurate 'per station' estimates. The last liberty was also justified by the period used for analyses (1948–2009) that was initially rich with data from well-developed gauge networks. **Figure 13** shows similar estimates but for the northwestern (Washington, Oregon, and Idaho) and southwestern States (Four Corners: Utah, Colorado, Arizona, and New Mexico).

Climatology of intense precipitation distribution for these mostly dry regions is very different from that for the eastern United States (cf., **Table 1**) and is therefore shown separately in **Table 5**. **Table 5** shows that 79% of all intense precipitation events in the northwestern United States are delivered by days with moderately heavy precipitation (over the entire CONUS this mean number is close to 50%). Days with precipitation in the range from 1 to 3 inches comprise another 20% (defined for the eastern two-thirds as heavy rain events, but here the significant fraction of these events (those in the range from 2 to 3 inches) can be easily quantified as very heavy according to the 'percentile' scale presented in **Table 1**). Only one percent of intense rainfall is classified into the greater than 3-inch daily rainfall category. Frequencies of only these rain events have increased during the past three decades compared to the previous three decades (**Figure 13**). The probabilities of rare daily rain events (shown in **Table 5**), and the inverse values that are customarily interpreted as approximations of return periods

Table 4 Characteristics of changes in heavy and very heavy precipitation across the global land areas depicted in **Figure 7**. All statements about statistical significance are based on 0.05 or higher levels of significance. Abbreviation ‘P’ is used for precipitation

Region	*Season*	*Period*	*Characteristics of intense P*	*Sign of the change*	*Comments*	*Sources*
Japan						
All nation	Annual	1890–1990	Years of 3 max. daily P per century	Increase	First report.	Iwashima and Yamamoto 1993
North of 37.5°N	JJA	1951–89	Above 100 mm d^{-1}	Increase		
South of 37.5°N	JJA			Decrease		Easterling et al. 2000
North, South, and all nation	Annual & JJA	1951–2011	Upper 0.3% of rain events	No Change	Significant decreases in precipitation totals and rain days are accompanied with no change or a weak increase in heavy and very heavy daily rain events. Nationwide precipitation intensity has increased by 12–15%/50 year.	Groisman et al. 2005 updated
			Daily intensity	Increase		
All nation	Annual and four seasons	1898–2003	Upper 10% of 4-hourly events	Increase	A century long increase by ~30%	Fujibe et al. 2005
China						
Northeast	JJA	1951–97	Above 50 mm d^{-1}	Decrease	Reported changes were statistically insignificant	Easterling et al. 2000
Southeast	JJA	1951–97	Above 100 mm d^{-1}	Increase		
North	Annual, warm, & cold; Four seasons	1951–2000	Upper 5% of rain events (upper 2.5% and 5% in Wang and Zhou)	Decrease		Zhai et al. 2005; Wang and Zhou 2005
West		1960–2001		Increase		
Southeast				Increase		
Mid–lower reaches of the Yangtze River				Increase		
Tibetan Plateau	Annual	1961–2005	Frich indices	Increase	Decrease in the central Plateau	You et al. 2008
India						
Western half	Annual and JJAS	1901–83	Above 100 mm	Increase		Easterling et al. 2000
		1910–2000	Upper 10%, 5%, & 2.5% of rain events Max 1,5, 30 day $\sum$	Increase	Decrease in the eastern half Nationwide increases outnumber decreases by two to one	Roy and Balling, 2004
West coast and Maharashtra		1901–2000	Above 75, 125 mm d^{-1}, annual maxim.	Increase		Joshi and Radjeevan 2006
Central Region		1951–2000	Daily events above 100 and 150 mm	Increase	Statistically significant	Goswami et al. 2006
Central Region		1901–2004		Increase	Statistically significant	Rajeevan et al. 2008
Other Asian countries and regions						
Middle East	Annual	1950–2004	Frich indices	No change		Zhang et al. 2005; Sensoy et al., 2007
Central Asia	Annual	1961–2000	Frich indices;	No change		Klein Tank et al. 2006
North. Pakistan			Max. 5-day rainfall totals	Increase	Statistically significant	
Sri Lanka				Decrease	Statistically significant	
Thailand	SON	1951–85	Above 100 mm d^{-1}	Decrease		Easterling et al. 2000
Indochina and Indonesia	Annual	1971–2005	Frich indices	No change	No coherent changes were found over the region	Caesar et al. 2011
		1961–98				Manton et al. 2001

Australia						
N.S.Wales and Victoria	DJF	1900–96	Above 50.8 mm d^{-1}	Increase	Strong and significant	Easterling et al. 2000
Southwestern tip of the continent	JJA	1913–98	Upper 0.3% of rain events	Decrease	Significant only at the 0.1 level	Groisman et al. 2005
Continent except the desert areas	Nov–Apr	1910–90	Upper 10% and 5% of rain events	Increase	But decrease in the Southwest	Suppiah and Hennessy 1998
	May–Oct			Increase	Insignificant change	
East and Southeast	Annual	1910–98	Upper 5% of rain events	Increase	Strong and significant	Haylock and Nicholls 2000
Southwestern tip				Decrease		
Sub-Sahara Africa						
Ethiopia and Eritrea	JJA	1951–87	Above 25.4 mm d^{-1}	Decrease	Decreases were statistically significant and strong	Easterling et al. 2000
Kenya and Tanzania	MAM	1940–67	Above 50.8 mm d^{-1}	Decrease		
Northern Nigeria	JJAS	1931–96	Above 25 mm d^{-1}	Decrease	Decrease after a change point, mostly between 1964 and 1972	Tarhule and Woo 1998
Sahel zone	Annual	1961–90	Maximum annual 5-day rainfall; Frich indices	Decrease		Easterling et al. 2003
Guinea, Conakry	Annual	1955–2006		Decrease	Statistically significant	Aguillar et al. 2009
D. Rep. Congo	Annual	1955–2006		Decrease		
Zimbabwe	Annual	1955–2006		Increase		
South Africa						
Southwest	JJA	1926–97	Above 25.4 mm d^{-1}	Increase	Strong and significant	Easterling et al. 2000
Natal	DJF	1901–97	Above 50.8 mm d^{-1}	Increase	Strong and significant	
Eastern half of the nation	Annual & DJF	1906–97	Upper 0.3% of rain events	Increase	Strong and significant	Groisman et al. 2005
Entire nation	Annual	1931–90	10 year return max. P in two 30 year periods	Increase	Significant increase over ~70% of the country	Mason et al. 1999
				Increase	Overview; No original analyses	Fauchereau et al. 2003
Central America	Annual	1961—2003	Frich indices	Increase		Aguillar et al. 2005
Caribbean	Annual	1958–99	Frich indices	Increase		Peterson et al. 2002
Brazil						
Nord-Este	MAM	1935–83	Above 100 mm d^{-1}	Increase		Easterling et al. 2000
Nord-Este	Annual	1911–2001	Upper 0.3% of rain events	Increase	Increases in both regions of Eastern Brazil were strong and statistically significant.	Groisman et al. 2005
North.Subtropics	Annual	1941–2001		Increase		
South and Uruguay	Annual	1941–2001		Increase		
South, Uruguay, and Paraguay	Annual	1960–2000	Number of days with $P > 10$ mm	Increase	Statistically significant trends around the La Plata Basin	Marengo et al. 2010
Southeast	Annual	1960–2004	Upper 1% and 0.1% of rain events	Increase	Trend is insignificant	Teixeira and Satyamurty 2011
South	Annual			Increase	Statistically significant trend	
South America beyond Brazil						
Ecuador	Annual	1960–2000	Frich indices for intense rainfall	Increase	Different indices give opposite signs along the Pacific Coast.	Haylock et al. 2006
Peru and Chile				Decrease		
North Argentina				Increase		

(*Continued*)

Table 4 Characteristics of changes in heavy and very heavy precipitation across the global land areas depicted in Figure 7 All statements about statistical significance are based on 0.05 or higher levels of significance. Abbreviation ‘P’ is used for precipitation—cont'd

Region	*Season*	*Period*	*Characteristics of intense P*	*Sign of the change*	*Comments*	*Sources*
La Plata Basin	Four seasons	1950–2000	Upper 25% of rain events	Increase	Increase in all seasons except the austral winter (JJA)	Penalba and Robledo 2010
Central Europe and Mediterranean						
Czech Rep.	Annual	1895–2006	Maximum daily P.	No change		Květoň and Žak 2008
	DJF	1961–2005	Max 1,3,5, 10, 20 daily totals; P in the upper 10% and 5% of rain events	Increase	Increase is mostly in the West	Kyselý 2009
	MAM			Decrease		
	JJA			Increase	Weak increase	
	SON			No change		
Austria	Annual	More than 50 years of data	Max daily P; upper 5 %, 1%, and 0.5% of rain events	No change	Among 31 analyzed stations, 20 had $\leq$70 years of data and 6 had $\geq$100 years	Villarini et al. 2011
Switzerland	Autumn Winter	1901–94	Events with return period $\geq$30 days	Increase		Frei and Shär 2001
United Kingdom	DJF	1961–2001	Days with $P \geq 15$ mm	Increase		Osborn and Hulme 2002
	JJA	1961–2000	Max. 5-day rainfall	Decrease		
	DJF	1958–2000		Increase		Haylock and Goodess 2004
Northern Europe	DJF	1958–2000	Upper 10% events	Increase	The trends were calculated on a station basis	Haylock and Goodess 2004
S. west and S. east	DJF	1958–2000	Upper 10% events	Decrease		
Europe south of 60°N	All but	1958–75	Above 60 mm d^{-1}	Decrease	Statistically significant	Karagiannidis et al. 2009
	JJA	1976–2000	Above 60 mm d^{-1}	No change	Insignificant decrease	
All continent	Annual	1946–99	Above 20 mm d^{-1} and upper 5% days	Increase	No increase in Southern Europe Weak average increase	Klein Tank and Können 2003
West of 60°E; mostly central	JJA	1901–2000	Frich indices of heavy precipitation	Increase	Statistically significant	Moberg et al. 2006
	DJF	1901–2000		Increase		
North and Central	Oct–Mar	1950–2009	Duration of wet periods	Increase		Zolina et al. 2012
Mediterranean and North and Central Europe	Apr–Sep	1950–2009		Decrease	But increase in France and Benelux nations	
South Poland, Thuringia, and Saxony	Annual, seasonal	1951–2006	Upper 5% and 10% precipitation events	Variable, regionally seasonally	Over Germany: increase Over southern Poland: mostly decrease, especially in JJA	Łupikasza et al., 2010
France	Two seasons	1960–2003	Annual daily maximum P	Increase	Results are inconclusive.	Cantet et al. 2011
Southern France	Annual	1949–2004		Increase	Statistically significant trend	Neppel et al. 2011
Spain	Annual	1951–95	Above 128 mm d^{-1}	Increase	Statistically significant	Alpert et al. 2002
Spain, Catalonia	Annual	1930–2006	10-year return period quantile	No change		Begueria et al. 2010
	Winter			Decrease		
	Spring			Increase		
Italy	Annual	1951–95	Above 128 mm d^{-1}	Increase	Statistically significant	Alpert et al. 2002
		1880–2002	Daily intensity.	Increase		Brunetti et al. 2004
			Upper 1% of daily events.	Increase	Increase only in the North	
Greece	Cold season	1950–2000	Upper 5% of rain events	Increase		Norrant and Douguédroit 2006
Israel	Annual	1951–95	Above 64 mm d^{-1}	No change		Alpert et al. 2002
North Israel		1930–90	Shape parameter of the Γ-distribution	Decrease	Land use change may cause some of these changes	Ben-Gai et al. 1998
South Israel				Increase		

Table 5 Climatology of the intense precipitation in the northwestern and southwestern (Four Corners) United States.

	Northwest, NW		*NW, west of 121.5° W*	*Four Corners*	
Precipitation range, mm	*Days with P year^{-1} stn^{-1}*	*Percent of events*	*Days with P year^{-1} stn^{-1}*	*Days with P year^{-1} stn^{-1}*	*Percent of events*
12.7–25.4	14.45	78.7	27.6	6.037	86.1
27.9–50.8	3.187	17.3	7.2	0.8683	12.4
53.3–76.2	0.5449	3.0	1.3	0.0884	1.26
78.7–101.6	0.1296	0.706	0.306	0.0156	0.223
104.1–127	0.0378	0.206	0.0914	0.0032	0.046
129.5–152.4	0.0119	0.065	0.0287	0.0008	0.011
>154.9	0.0093	0.051	0.0198	0.0004	0.005
All days with intense P	18.37	100	36.50	7.014	100

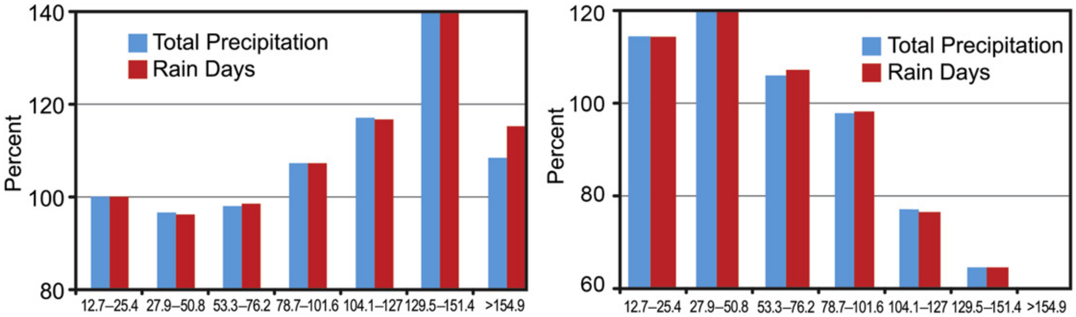

Figure 13 Same as in **Figure 11** but for daily precipitation events (COOP network) over the northwestern (Washington, Oregon, and Idaho; left) and southwestern (Four Corners: Utah, Colorado, Arizona, and New Mexico; right) United States.

(e.g., for events above 5 inches, this return period estimate looks like 100 years), should be interpreted with caution due to large spatial heterogeneity of precipitation pattern across the Northwest. Our estimates are averaged over 320 long-term stations of three states. Therefore, stations along the Pacific Coast and windward slopes of Cascades and Olympic Ranges reported most of regional extreme precipitation events, while the stations eastward of the coastal mountain ranges did not deliver many extreme rainfall events and participating in regional averaging reduced the probabilities of event occurrence shown in Table 5. When we selected the eastern boundary of the 'northwestern-most' United States by 121.5 °W (i.e., separating 126 stations in the wet coastal regions of the Oregon and Washington States), our counts of the very heavy and extreme daily precipitation events of 4 inches and above practically did not change, but their frequencies per year per station in the region increased to 0.091, 0.029, and 0.020 for events between 4 and 5, 5 and 6, and above 6 inches, respectively. Analysis of the results presented in Table 5 and Figure 13 provides an explanation of the peculiarity of the northwestern United States revealed in Figure 3. Only in the Northwest, Figure 3 showed a relative increase in the fraction of moderately heavy precipitation events compared to other intense rain events (above 25.4 mm). In fact, the frequency of the moderately heavy precipitation events (79% of all days with intense precipitation) did not change. The number of days with precipitation in the range from 1 to 3 inches decreased (another 20% of all days with intense precipitation) and this decrease predefined the sign of changes in the fraction of moderately heavy precipitation events within the intense rain events distribution. Changes in the upper one percent of intense rain events distribution were in a 'right direction' (increase, as in other regions of the eastern and central United States). However, their increase was insufficient to overweigh a decrease of the less intense but 20 times more numerous rain events (cf., Table 5 and Figure 13).

Southwestern United States (Four Corners States) is a dry region compared to all other parts of the CONUS. As a result, the scale of intense precipitation is shifted to lower ranges and on average the rain days with totals in the range of 12.7–25.4 mm occur here six times per year and comprise 86% of all days with intense precipitation. Another 12.5% of rain events come in the range from 1- to 2-inch day^{-1} and these events occur less than one per year (Table 5). Frequency of these events as well as the frequency of the two following ranges has increased in the past three decades compared to the previous period (Figure 13), while the frequency of rain days with daily totals above 4 inches decreased. It should be noted that whatever the spatial inhomogeneity across the region is (e.g., mountains against the lowlands and the low elevation biases of the GHCN-Daily sites used in our analysis), the total number of catastrophic rain events reported by 487 long-term stations in this region during the past 62 years was 97, 23, and 11 for 4 to 5, 5 to 6 and for rain events above 6-inch day^{-1}, respectively. These events (according to Figure 13) had occurred more frequently in the first three decades after World War II than thereafter.

5.03.2.7 Studies That Used a Parameterized Approach to Extreme Precipitation over the United States

DeGaetano (2009) analyzed the 30 maximum daily accumulation precipitation totals at the 1061 long-term high quality stations of the US Historical Climatology network during the

1950–2007 period. The analysis was conducted four times using 30-year running intervals, lengthening periods (30, 40, etc.) and for the starting dates of 1950 and 1960. At each site and for each period, he estimated the parameters of the GEV distribution (cf., Kharin and Zwiers 2005) that fit these maximums and assessed the changes in these parameters with time over the CONUS. Such analysis allows estimating the pattern of the return period precipitation amounts and their trends. His analysis revealed the regions where the changes in the GEV location parameter are significant (increase) and that (a) other GEV parameters did not change systematically with time and (b) there are regions (California, Intramontane regions, and Southeast) where no changes in extreme precipitation distribution were revealed. Areas where a significant increase in the return precipitation amounts was observed coincide with the areas shown in **Figure 10** (the northeastern quadrant of the CONUS) with an addition of the Pacific Northwest (coastal areas). After analysis with sub-division of the northwest into wet humid and dry parts with appropriate recalculation of the event frequencies (**Table 5**), this increase is also supported by estimates shown in **Figure 13**. It is important to note that the estimates provided by DeGaetano (2009) (precipitation amounts for 2-, 30-, and 100-year return intervals) directly address the concern of the civil engineering community. They are generally supported by independent estimates that do not rely upon any assumptions about the distribution of extreme precipitation, which strengthens the conclusions of this study and increases its practical importance.

Kunkel et al (2013) presented several metrics used to estimate extreme precipitation changes over the CONUS, including one based on time varying peaks over specified thresholds using statistical extreme value analysis (Tomassini and Jacob 2009; Cooley and Sain 2010; Maraun et al. 2009). For each year, the station-specific thresholds were set to the 97th percentile over days with at least 1 mm of rainfall (i.e., on average for the CONUS, at one to three rain events per year). Next, the exceedances of these thresholds were approximated with a dynamically changed generalized Pareto distribution, and possible changes during the 1948–2010 period in one of its parameters responsible for increase/decrease in 20-year return period values were tested at each long-term GHCN-daily station. This statistical analysis shows that about 76% of all CONUS stations experience increases in extreme precipitation, with 15% showing a statistically significant ($P < 0.05$) increase based on station-specific two-sided tests. A field significance test based on resampling entire years of data (to preserve spatial structure and within year seasonal patterns) was statistically significant ($P < 0.001$). Across the eastern two-thirds of the CONUS these exhibit a high degree of spatial coherence. Regions with greater numbers of stations with decreases are of smaller spatial extent and include the coastal northwest (cf., **Figure 13** for heavy precipitation). Moreover, when mapped, the results of this analysis indicate that everywhere across the CONUS extreme precipitation (20-year return period values) has increased during the past 62 years; however, not all of these changes can be claimed to be statistically significant. In particular, this type of analyses claims that over southern California and the Four Corners States the extreme precipitation has increased, while direct assessments of changes in extreme precipitation for California (Bonnin et al. 2011) and the Four Corners States (**Figure 13**) do not confirm this claim.

The above brief intercomparison of parameterized (distribution-based) and direct approaches shows that in the regions where a linearity of changes in heavy, very heavy, and extreme precipitation has occurred (the signs of changes are the same and only the rates of changes can be different), all approaches give noncontradictory similar results. However, when extreme distribution parameter estimates (fitting the distribution curves) are observed in the regions where nonlinear changes in intense precipitation have occurred (northwest, southwest, Mountains), the results based on this fitting (specifically our conclusions about changes in extreme precipitation based on this fitting and follow up extrapolations) may be compromised. For example,

- In the regions along the Pacific northwest coast, extreme rainfall has increased but analyses based on heavy rainfall in this region will generate opposite conclusions (cf., **Figure 13**, left panel and DeGaetano 2009 versus Kunkel et al. 2013).
- Extreme rainfall in the Four Corners States became much less frequent in the past three decades (**Figure 13**, right panel), but analyses based on heavy and very heavy rainfall in this region again generate opposite conclusions (Kunkel et al. 2013).

Finally, in the regions where different genera of extreme rainfall may occur (cf., Southeastern United States) their tendencies may well be different (Kunkel et al. 2012) and even have an opposite sign (cf., Southeastern United States, **Figure 2**).

5.03.2.8 Results Based on Daily Data versus Hourly Data

Precipitation is not a contiguous process and even in the days with extreme precipitation above 155 mm over the CONUS on average there are 9 h without rainfall (**Figure 14**). Therefore, assessments that use the daily time scale (daily totals) still can be considered incomplete answers to the questions about the precipitation dynamics especially during the warm season when rainfall immediately and in a multifaceted manner contributes to the surface water budget. As **Figure 14** shows for northern Eurasia, short-duration rainfall is most frequent in summer when its significant fraction comes in convective rainfall form (Sun et al. 2001). Unavailability of large long-term data sets with sub-daily time resolution has so far prevented global analyses of how the global change would manifest itself across the smaller time scales, specifically, at the hourly time scale during the warm season (i.e., for rainfall). The importance of this time scale is difficult to estimate because there is a large difference in impact on environment and/or the human-built infrastructure if, for example, a 25 mm day^{-1} rainfall total in fact occurred in an hour or less. The consequences for soil erosion (USSWCS 2003), flash flooding (Brooks and Stensrud 2000; especially in urbanized areas), and infrastructure damage (cf., Changnon and Westott 2002; Villarini et al. 2009) could be very different.

Changes in precipitation extremes under greenhouse warming are commonly assumed to be constrained by changes in the amounts of precipitable water in the atmosphere (Allen and Ingram 2002; Trenberth et al. 2003; Trenberth 2011; IPCC 2007). Global climate models generally predict only marginal changes

Mean rainfall duration in days with rain over the former USSR (hours)

April	
Kamchatka	1–11
Russian Arctic	8–9
Forest and steppe	5–8
Central Asia	4–6
July	
Kamchatka	8–9
Russian Arctic	7–8
Forest and steppe	2–5
Central Asia	0.5–2
October	
Kamchatka	7–8
Russian Arctic	7–9
Forest and steppe	5–12
Central Asia	4–6

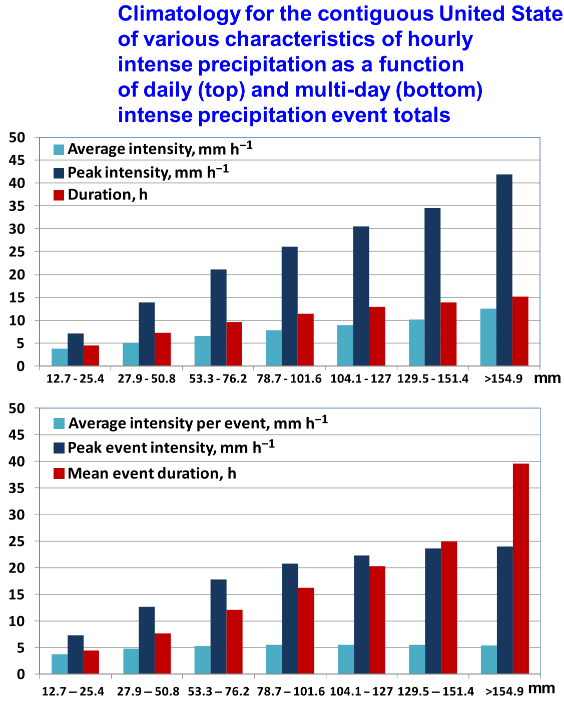

Figure 14 Precipitation duration in the extratropics estimated by recording gauges in northern Eurasia (Lebedev 1964) and the United States (archive of Groisman et al. 2012). Only intense daily events (>12.7 mm) are considered for the CONUS.

in relative humidity (Bony et al. 2006; Min et al. 2011), implying that the actual amount of atmospheric precipitable water is scaled with the water vapor content of saturation, which is governed by the Clausius–Clapeyron relation. The common belief is that the mean precipitation change is not obeying this relationship and the changes may be less than predicted (cf., Trenberth 2011). Indeed, changes in heavy ('extreme' in the language used by the modelers) daily precipitation in global climate models seem to be consistent with the 7% increase per degree of warming given by the Clausius–Clapeyron relation (IPCC 2007; Pall et al. 2007). In the absence of global analyses, we present below the recent findings accumulated in West Europe and the CONUS. In the former USSR (and currently in the Russian Federation), the dense network of the recording rain gauges exists and was used for climatological studies (e.g., Lebedev 1964), but has never been used for climate change studies.

Using the 99 years of hourly precipitation time series at de Bilt, the Netherlands, Lenderink and van Meijgaard (2008) tested how the mean daily and maximum hourly rainfall intensity are changing with the surface air temperature variations. They concluded that when the daily mean temperature exceeded 12 °C, hourly precipitation extremes increased with an increase in temperature twice as fast as expected from the Clausius–Clapeyron relation. Furthermore, analyzing the regional climate model output for central Europe, they found that this increase with summer surface air temperature in 1 hour precipitation extremes typically exceeds 10% K^{-1}, and in a large area even 15% K^{-1}, while daily extremes typically increase by 5–10% per degree (i.e., in line with the Clausius–Clapeyron relation).

In the previous subsection we describe analyses of extreme precipitation changes over the CONUS with time conducted by Groisman et al. (2012). Here, we describe a byproduct of this study when the same comparison between the last three decades and the previous three decades (and numerous other possible partitions in two equal groups of years) was conducted to assess the possible changes in the internal precipitation structure, such as mean and maximum hourly precipitation rates and precipitation duration (in hours). It was found that the climatology of these characteristics is systematically changing with increase of the rainfall range (cf., Figure 14). However, within each preselected range of daily or event totals, Groisman et al. (2012) found that mean and maximum hourly intensity and duration of precipitation daily and multiday events do not noticeably change. This conclusion remained valid with all partitions (by time, by season, or by any other external factor that we employed) and for each of the nine large regions of the CONUS shown in Figure 4(b). In Figure 15, we present one of these comparisons made several years ago (thus, no data after 2007 were used) for the eastern half of the CONUS east of the Mississippi River.

Results shown in Figures 11 and 15 hint that while very heavy and extreme rain days and events became more frequent with time, the processes that control the internal structure of these events, e.g., peak hour rain intensity and its duration, do not change. Eventually, in the regions with increasing frequency of extreme rainfall, the frequency of higher peak rain intensity will be observed but this will occur 'orderly' following the appropriate changes in daily rainfall intensities. The above conclusion is based on the various analyses for diverse regions and seasons but only for the conterminous United States. Thus, it can well be that in the tropics or in the polar regions, it will not be valid or, at least, the future users of

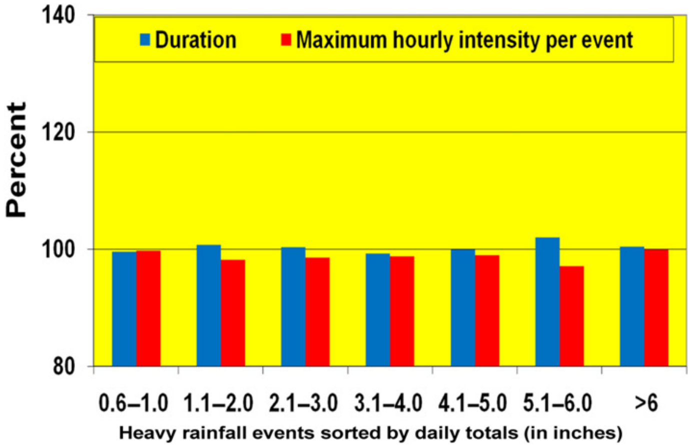

Figure 15 Comparison of heavy rainfall characteristics in the 'warm' and 'cold' Northern Hemisphere years in the eastern half of the CONUS (east of the Mississippi River). Data of 1715 hourly precipitation (HPD) stations for the 1948–2007 period were used in this comparison. Warm and cold years' rainfall records were scaled to the same number of stations available in both 30-year-long periods with the difference in the mean annual surface air temperature, ΔTNH, equal to 0.54 °C. Heavy daily rainfall events are sorted by the rainfall totals in the same manner as in **Figures 2 and 11** but the *x*-axes is in inches.

these results need a leap of faith to assume such development without testing it.

5.03.2.9 Prolonged No-Rain Periods

Karl and Knight (1998) and subsequent studies (Easterling et al. 2000; Stone et al. 2000; Groisman et al. 2004, 2005) all show that most of the precipitation increase over the United States, Mexico, and Canada occurs due to an increase in the frequency of intense precipitation while the frequency of days with average and light precipitation does not change or decreases. The tendencies, which emerged during the past 35–40 years with a disproportional increase in precipitation coming from intense rain events (Groisman et al. 2004, 2005), should lead to breaks in the parallel increase/decrease of both total precipitation and precipitation frequency. For the United States, this break was first reported in the mid-1970s by Sun and Groisman (2004) and for the northeastern quadrant of the conterminous United States was *projected* by Semenov and Bengtsson (2002), and thereafter confirmed by Groisman et al. (2005). Specifically, for the northeastern quadrant of the United States, the last authors reported an increase (or no change) in precipitation totals but a decrease in the number of days with precipitation. If continued, this decrease in precipitation frequency may lead to an increase in the frequency of another potentially dangerous type of extreme events: prolonged periods without precipitation (even when the mean seasonal rainfall totals increase). Groisman and Knight (2007, 2008) investigated whether this unfortunate development is already occurring in the warm season during the past several decades over North America south of 55°N, for the same period when we begin observing changes in frequency of intense precipitation events (i.e., since *c.*, 1970). North of 55°N, the station network density is generally insufficient for analyses used below. But, indirect evidence, first of all, an increase in areas consumed by forest fires in northwestern Canada (Gillett et al. 2004) and Alaska (Groisman et al. 2007), suggests a similar development in the northwest of North America.

The most detailed description of the approach they used and results are provided in Groisman and Knight (2008) for conterminous United States. However, the same analyses had been simultaneously conducted for Canada, Mexico, and Russia. In Russia, the analyses were conducted only for the regions south of 60°N in the European part of the country and south of 55°N in the Asian Russia for the same reason as for North America (cf., the previous paragraph). The findings of this assessment are as follows:

Over a substantial part of the conterminous United States (specifically, over the Eastern United States and the southwestern quadrant of the CONUS) during the 1967–2006 period, the frequency of occurrence of 30- (Eastern United States) and 60-day-long and above (Southwest) no-rain periods substantially increased (by 1.1 and 4.3 % per 40 years, respectively). These increases should be compared with the average fraction of occurrence of these dry episodes (1.5 and 14%, respectively). This means that over the Eastern United States, the frequency of these episodes nearly doubled. For the Northwestern quadrant of the CONUS and the humid Great Lake Area (as well as for adjacent regions of western Canada south of 55°N), for any duration of the dry episodes considered, we did not find statistically significant trends at the 0.05 level (using two- or one-tailed *t*-tests) in the fraction of the warm season consumed by these episodes.

The observed changes in the occurrence of the prolonged no-rain periods are not restricted to the CONUS but are expanded to the adjacent areas of northern and eastern Mexico and southeastern Canada (Groisman and Knight 2007; Figure 16). Specifically,

- Over *northern Mexico*, changes in the duration (in percent of the warm season, which is practically the entire year there) of prolonged dry periods 60 or more days without rain has increased by 9.4% during the past 40 years and this increase has been statistically significant (the long-term mean frequency of such dry episode is 49%).

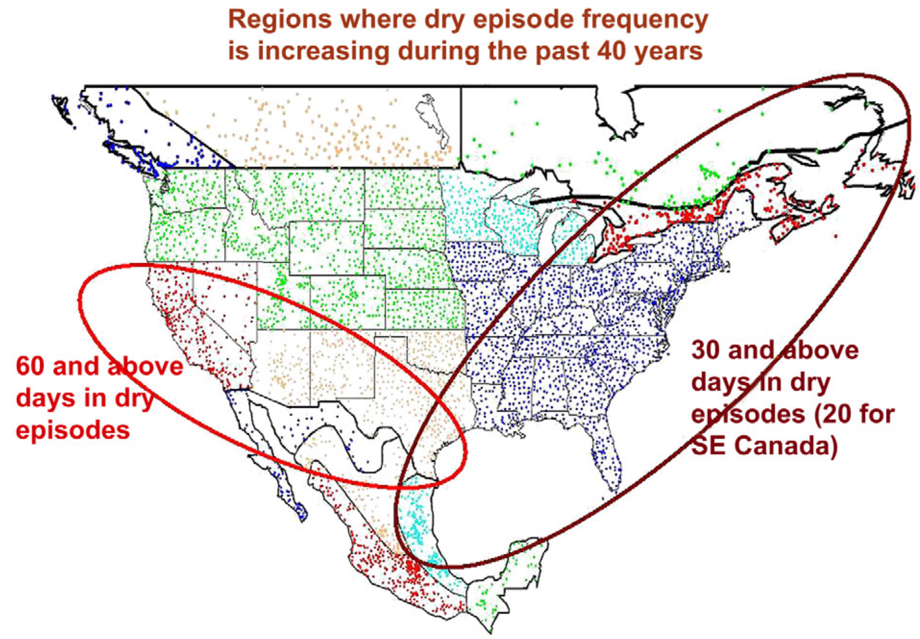
Regions where dry episode frequency is increasing during the past 40 years
60 and above days in dry episodes
30 and above days in dry episodes (20 for SE Canada)

Figure 16 Schematic summary of statistically significant results showing the increase of prolonged dry day episodes across North America during the 1967–2006 period. Dots show the station locations with daily rainfall and temperature data used in the analysis and the dot colors (and solid lines) outline the regional boundaries within which the authors evaluated regional estimates of no-rain periods (Groisman, P. Ya., and R. W. Knight, 2007: Prolonged dry episodes over North America: new tendencies emerging during the last 40 years. *Adv. Earth Sci.*, **22** (11), 1191–1207.).

- Over *the humid Gulf Coast of Mexico*, there was a statistically significant increase in the frequency of prolonged dry periods, 30 or more days without rain, by 7.3% per 40 years (the long-term mean frequency of such dry episode is 20%). The increase here was mostly defined by a group of dry years in the late 1990s. In 1998, the total duration of prolonged dry periods 30 or more days without rain in this part of Mexico was extremely large, being twofold higher than the average (40% of days annually against the average 20% of days annually). It is worthy to note that this was a year of an extraordinary strong El-Niño.
- Over *southeastern Canada*, where precipitation is quite frequent, during the post-World War II period, most of the stations have not seen 30-day intervals without precipitation. Therefore, we lowered the criterion for minimum length of dry episode duration for the region to 20 days. These dry episodes are infrequent occupying on average slightly more than 1% of the warm season (1.2%). Therefore, while a twofold increase in the frequency of dry episodes during the 1967–2005 period (by 1.1%/40 year) is statistically significant at the 0.05 level, practical significance of this change can be questioned.

Over southern Siberia and Russian Far East (Figure 17 left panel), the frequency of dry episodes above 30 days during the warm season is quite small. This frequency had doubled during the 1956–2005 period. While the duration of the warm season is short (from four to five months), the mid-summer insolation and maximum temperatures are high. The prolonged no-rain episodes, combined with a general decrease (or no change) in rainfall (cf., Figure 1, top panel), create a substantial water deficit, increase the forest fire danger (Groisman et al. 2007), and the increase in areas consumed annually by the actual forest fires (Conard et al. 2002; Korovin and Zukkert 2003; updated).

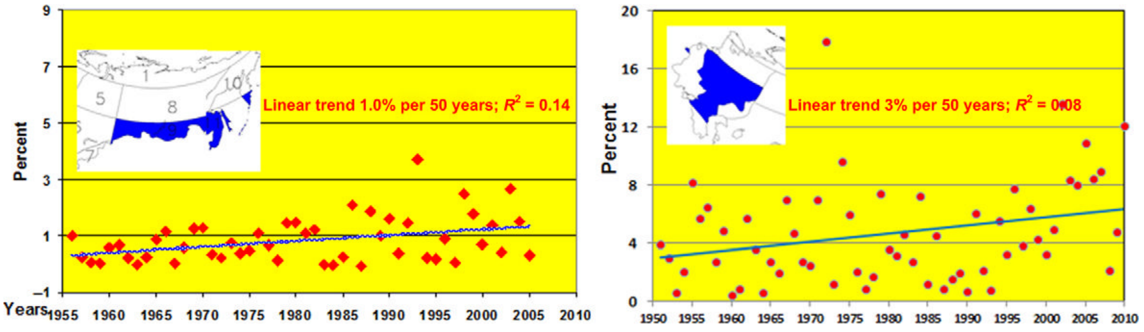

Figure 17 Dry episodes above 30 days during the warm season over (left) Asian Russia east of 85°E and south of 55°N and (right) European Russia south of 60°N. Both linear trends are statistically significant at the 0.05 level.

The European part of Russia south of 60°N (ER) spans from the taiga zone in the north to dry steppe and semi-deserts in the southeast. The growing season is 6 months on average and in the southern steppes can reach 8 months. The northern part of the region is considered a zone of steady agricultural production while in the south, in the region of the most fertile soils, droughts are frequent. Over this particular part of Russia during the past 60 years precipitation conditions noticeably improved: annual precipitation has increased (Bogdanova et al. 2010), natural runoff of the major river, Volga, has increased (Georgievsky et al. 2002), upper layer soil moisture during the warm season has increased (Speranskaya 2011), and the Palmer Drought Severity Index over the region has increased throughout the twentieth century (Dai et al. 2004). However, **Figure 17** (right panel) shows that during the same period of 'improvement' in the mean regional hydrological conditions, intraseasonal variability of rain events remained high and the frequency of prolonged periods without rain has increased. This signal was one of several that preceded a catastrophic drought in July–August 2010. There were drier summers over ER in the past (e.g., 1972 and 2002) than in 2010. However, in 2010, a strong water deficit due to a prolonged no-rain episode coincided with unprecedented very high surface air temperatures (in 2010, mean July–August surface air temperature over ER was 2 °C higher than in the previous record in 1972 and more than 5 °C above climatological mean values). In many locations across European Russia, absolute temperature records were exceeded and dramatic thresholds such as 'hot nights' were first reported as far north as at 60°N in St. Petersburg. This combination of a prolonged no-rain period and high summer temperatures decimated crops and caused numerous forest and steppe fires that in some cases spread toward settlements causing property and human life losses (Mokhov 2011). Smog over Moscow affected health of millions citizens and indirectly caused premature deaths (estimated to be of the order of 50 000). Extremely hot nights are harmful for human health when (according to Kalkstein and Davis 1989) the temperature conditions throughout the entire night even into the early morning do not drop below 25.9 °C (75 °F). They are closely correlated to the increase of detrimental health conditions (heart attacks, strokes, and, when combined with air pollution, asthma strikes). Over ER, such nights are very infrequent (**Figure 18**). Therefore, nearly all private houses and apartment buildings are not equipped with air conditioning. However, *10 years prior to the heat spell of 2010, the number of such nights nearly quadrupled*. This change was left unnoticed. Lessons were learned by Western Europeans who paid dearly during the heat spell of 2003, making them much better prepared for the next heat spell of 2006. However, a similar scenario was not expected to be relevant for the colder climate of ER and no preparations were made. Therefore, when the 2010 hot spell hit the cities in central ER (including the national capital), the losses, including human life losses were significant.

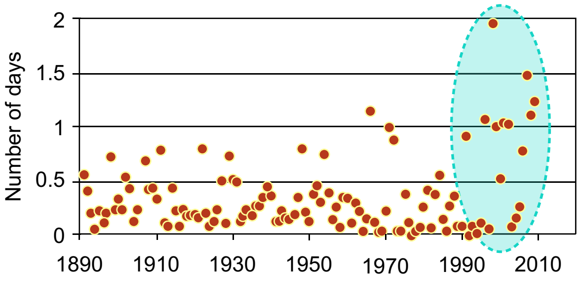

Figure 18 Number of days with 'hot' nights (when minimum daily surface air temperatures remain above 23.9 °C) area-averaged over ER south of 60°N during the 1891–2009 period. This number for 2010 exceeds five. These days closely correlate with an increased mortality of unprotected population.

Such weather conditions were absent during the period of instrumental records and extremely rare during the past millennium. However, for example, all weather anomalies described in old Russian Yearbooks ('Letopisi') for 1092 were repeated in 2010.

During the past 50 years, an increase in precipitation and soil moisture over ER was observed, but mostly overlooked were the concurrent changes that at the same time: (a) changes in the extratropical atmospheric circulation became more favorable to the blocking conditions over northern Eurasia (Mokhov 2011), (b) earlier spring onsets and winter thaws have gradually made a larger fraction of water resources accumulated in the previous seasons unavailable for the next summer season (Bulygina et al. 2011; Groisman et al. 2011), (c) areas affected by agricultural droughts were increasing (Meshcherskaya et al. 2011), (d) frequency of occurrence of prolonged ($\geq$30 days) no-rain periods was increasing (**Figure 17**), and (e) the number of days with 'very hot' nights with minimum temperatures $\geq$23.9 °C became disproportionally large in the past decade. Of course, nobody could predict the size and timing for the weather anomaly over ER in 2010 using climate change considerations. However, the ongoing climatic changes (including the severe heat wave outbreaks in Western Europe) staged the scene for it over ER and increased its probability.

5.03.3 Conclusions and Recommendations

In this chapter we investigated the current state of knowledge about the contemporary changes (mostly during the post-World War II period) of intense precipitation over the global land areas. It looks like these changes in the extratropical land areas were expected from theoretical considerations and their general features have already been reproduced (and projected into the future) by the most advanced contemporary global climate models (Meehl et al. 2007). However, details of these projections differ from model to model and it is not clear what will happen at the boundaries of the regions where these models hint to an increase in both intense precipitation and 'drier' conditions. Observations suggest that the area of such regions is significant over the mid-latitudes of the northern extratropics and includes a large fraction of the conterminous United States (cf., **Figures 10, 11, and 16**; Groisman and Knight 2008), southern Europe and Mediterranean (IPCC 2007; Zolina et al. 2012; **Table 4**), and a large swath of the northern Eurasia forest-steppe and taiga areas (cf., **Figures 1**, **Table 2**, and **Figure 17**; Groisman et al. 2009). How the changing structure of the hydrological cycle in these areas will manifest itself, affect the environment, and human well-being is an area of active current studies. In these studies, empirical assessments monitoring and trend analyses play an important role. They allow confirmation of theoretical considerations quantifying and refining them and deliver the knowledge about the here and now of the present state of the regional hydrological cycle and its dynamics.

A serious impediment for the studies of long-term changes in intense precipitation is a deficiency of comprehensive data sets of homogeneous time series from dense national meteorological networks available for international use. In the regions where such networks do not exist, we cannot complain because it takes time and resources for their establishment, and decades before they become useful for climate change assessments. But restricted access to the national network data in the regions, where these networks do exist, hampers reliable judgments about the most dangerous component of intense precipitation changes, the changes in the frequency and intensity of damaging extreme rain events. For example, the national precipitation network of Germany consists of more than 6000 stations (cf., Tomassini and Jacob 2009; Zolina et al. 2012), while the international (both European and global) archives have only 130 stations. Compared to two stations from Poland and one station from the Czech Republic, this is a good sample, but any study of rare extreme convective thunderstorms over these countries will be hampered by a danger of delivery of results that are nonrepresentative for central Europe. It does not help that the Global Precipitation Climatology Center (http://gpcc.dwd.de; Rudolf et al. 2011) most probably has this information (or an access to it) because the Center charter restricts dissemination of the station data to the international science community. The consequences of this impediment are (a) the focus of this chapter on the regions where we have unrestricted access to precipitation data and (b) an inability of the international scientific community to contribute to assessment of intense precipitation changes in the regions where these changes have occurred, were dramatic, and seriously affected the society. These regions appear on the screen only when something horrible happens (e.g., 2010 flooding in Pakistan). It would be much better if the analyses of intense precipitation changes and their possible consequences were made prior to such events. '*Informed means armed*'.

Final Notes. A few precautions advised to the researchers of intense precipitation changes were presented throughout the chapter. They include:

- There is a relationship between the network density at hand and the upper percentile (absolute rainfall) values whose changes the researcher can access (cf., the discussion on this matter in Groisman et al. (2005, 2012)). Both aspects are important. For example, scientists who declare the absence of heavy precipitation changes over the United States using 200 stations (instead of 6000 long-term stations) that are representative for less than 5% of the CONUS territory are not dissenters or skeptics but simply did not prepare well for their study.
- Light precipitation events are not consistently documented with time in many countries (**Figure 6**; Groisman et al. 1999). Precautions must be taken to avoid their impact on the artificial changes in the frequency of heavy precipitation. This precaution is especially important for high latitudinal countries (Canada, Russia, and Fennoscandia).
- Up to present, most (nearly all) observational results *and* the GCMs projections conveyed the information about changes in the frequency of heavy (sometimes very heavy) precipitation events. This is true even when nearly all climate modelers liberally use the term 'extreme' in description of their results. The *request* of the hydrologic and civil engineering communities to advise about changes in frequency and intensity of the actual extreme events (that cause real infrastructure damage and harm to human life) is not yet addressed to satisfaction and is an area of active ongoing studies. Those of these studies that focus on monitoring and documenting changes (i.e., based on observational data analyses) have a chance to succeed only in the regions with dense networks of long-term meteorological stations available to the national and international scientific communities (cf., achievements described above for the CONUS in Sections 5.03.2.4.6, 5.03.2.6, and 5.03.2.7). Of course, there are other approaches that can be used to address the request of this group of users that include regional high-resolution climate modeling and paleoclimatic and physical boundary considerations. These approaches, however, are beyond the focus of this chapter.

Summarizing, we conclude that over most of the extratropical land areas in the post-World War II period, increases in the frequency of heavy and very heavy precipitation events have occurred (**Figure 7** through 12, **Table 4**, Sections 5.03.2.3, 5.03.2.4, 5.03.2.5, 5.03.2.6, and 5.03.2.7). Over a sizeable part of mid-latitudes at the same time the frequency of the prolonged no-rain periods during the warm period has increased too (**Figures 16 and 17**; Zolina et al. 2012). Finally, for the regions with a dense network of long-term precipitation time series, observations support one of the major conclusions of climate modelers (Meehl et al. 2007; Trenberth 2011) about a general increase of precipitation intensity (cf., **Figure 19**).

In attempts to project prolonged extreme events (such as droughts and floods) in a given season, climatologists used to look for their precursors in the Earth system 'memory' that include anomalies in sea ice (SI) and snow cover extents (SCE), sea surface temperature (SST), and soil moisture and for their patterns (e.g., Southern Oscillation). However the major 'memory' component of the Earth system is the Earth Climate System itself. It began changing (IPCC 2007) and is not anymore a constant factor: SST, SI, and SCE anomalies of the past now became 'climatology' and it is time to include this new reality in our analyses of the frequency and intensity of extreme events. Apparently, when looking for extreme events occurrence one has to carefully select climatological variables that can be considered as precursors of these events and the changes in mean surface air temperature and precipitation may not be the best among them. Moreover, the characteristics of extreme precipitation and streamflow events that are commonly used in some segments of the scientific community, such as maximum annual precipitation (streamflow) values, are not an optimal choice and, in fact, may be misleading in the areas where increases in precipitation intensity and prolonged no-rain intervals simultaneously occur. Most of the CONUS is one of these such regions (cf., **Figures 10, 12, 16, and 19**, top panel).

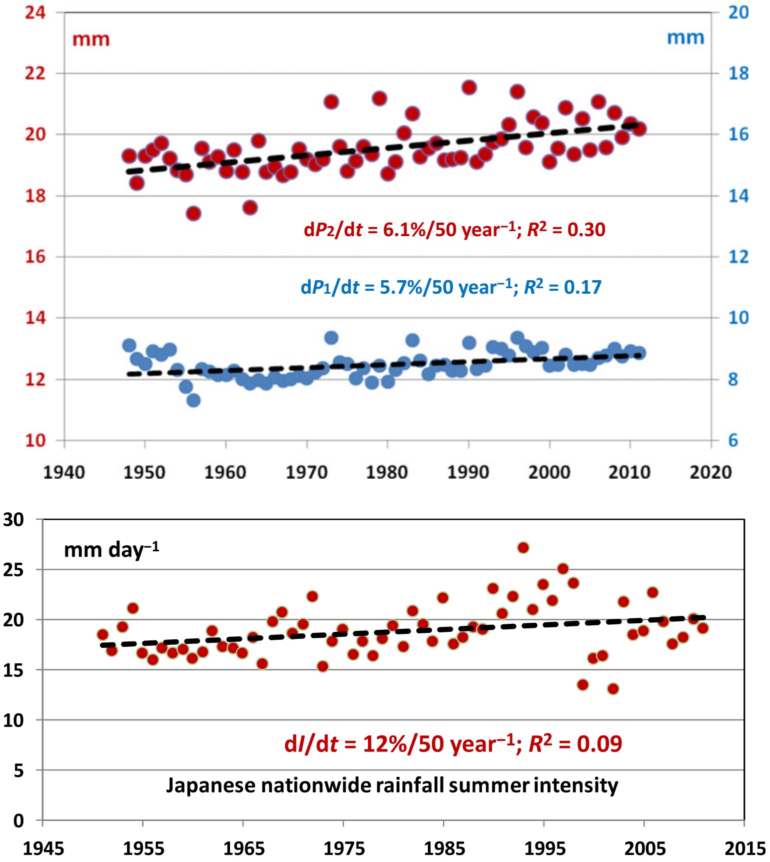

Figure 19 (Top) Mean daily precipitation, mm, per event that comes with 1- and 2-day-long events over the CONUS. The estimates of precipitation intensity in 1-day-long (P1, mm day^{-1}) and 2-day-long (P2, mm (2 days)$^{-1}$) are based on all precipitation events above 0.5 mm at ~6000 long-term US cooperative stations during the 1948–2011 period (updated archive of Groisman et al. 2012). P1 and P2 were selected to be nonoverlapping events (1-day events are not included in the 2-day events) and together contribute approximately 60% of nation precipitation totals. (Bottom) Mean summer (JJA) rainfall intensity, mm day^{-1} over Japan. Estimates of the annual precipitation intensity over the country also show an increase (with the mean rate of 14% 50 year^{-1}) but are not presented here due to our concerns about the instrumental homogeneity of the cold season precipitation measurements in this country after introduction of automation (tipping bucket rain gauges) in the early 1970s and thereafter.

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5.04 Orographic Precipitation, Freshwater Resources, and Climate Vulnerabilities in Mountainous Regions

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5.04.1 Introduction

Almost 25% of the world's population lives in tropical mountainous regions, and about 60–70% of the world's population relies on mountains for freshwater needs ranging from drinking water to food production, ecosystem services, and industrial use (United Nations 2002 International Year of the Mountains, http://www.mountains2002.org). Onishi et al. (2007) report that 60% of the freshwater resources input to China's Yellow River originated from its headwaters, and Thurow et al. (1998) estimated that over a billion people depended directly on the sustainability of steep lands for their subsistence. About half of the world's freshwater resources come from mountains, and a significant fraction of the world's food production takes place in the alluvial plains at the foothills of major mountain regions (e.g., Garrido and Dinar 2008; Nellemann et al. 2009). Changes in precipitation regimes associated with land use/land cover changes and population pressure in the continental highlands of the tropics could lead to increased aridity of alpine environments, decrease in groundwater recharge, and runoff production, thus potentially altering the hydrological regimes of downstream regions including some of the world's major river basins (e.g., Ganges, Indus, and Amazon). Mountain ecosystems are controlled by complex temperature–moisture conditions in the lower troposphere and are especially vulnerable to hydroclimatic variability and change. Tropical montane forests (TMFs), and tropical montane cloud forests in particular (TMCFs; see Chapter 5.5), combine high biodiversity and endemic species, with the tropical Andes having Earth's highest biodiversity (Krajic 2004; Myers et al. 2000, among many others). With worldwide distribution and strong environmental and climatic gradients, mountains are elevated observatories where the impacts of climate variability and longer term change might be first detected (Kupfer and Cairns 1996; Still et al. 1999; Foster 2001). Upward migration of alpine plants and alpine tree lines that has been found in several parts of the world is most likely caused by local and/or regional temperature increases and water stress impacts, particularly rising cloud base levels, decreasing stratus clouds and fog, and consequently decreasing rainfall, especially light rainfall (e.g., Peñuelas and Boada 2003; Malanson and Cairns 1995). Changes in cloud base are implicated in large-scale changes in animal communities (e.g., Pounds et al. 1999; Thomas et al. 2004) and amphibian declines (e.g., Pounds and Crump 1994; Pounds et al. 2006). Paleoecological evidence shows that montane communities have responded dramatically to past climate and may face unprecedented challenges in the future (Bush and Silman 2004; Bush et al. 2004). Importantly, estimates of the effects of global climate change on biodiversity in montane systems are poorly constrained because of poor understanding of species and ecosystem responses to climate (Malcolm et al. 2006; Thomas et al. 2004). Furthermore, nonlinear interactions among precipitation, vegetation, and soils have a significant impact on erosion processes and sediment yield in mountainous regions, which in turn affect ecosystem stability (e.g., Whol et al. 2012; Roering et al. 2003; Inbar and Llerena 2000).

In the water resources literature, mountains are popularly referred to as nature's freshwater towers [http://www.banffmountainfestivals.com/summit/2003/themes/]. This conveys the idea that freshwater released and stored at high elevations is delivered to lowlands and downstream ecosystems much in the same way that man-made water towers drive potable water distribution systems. The imagery stems from the observed increase in rainfall with elevation upwind mountain crests, which can be explained to first order by the forced (enhanced) lifting (cooling) of moist air to the lifting condensation level (LCL) forming (orographic) clouds, which over time produce precipitation with a significant increase (orographic enhancement) relative to adjacent low-elevation areas (Figure 1). Large arid or semiarid plateaus and valleys lay on the leeside (relative to the regional climatology of moisture

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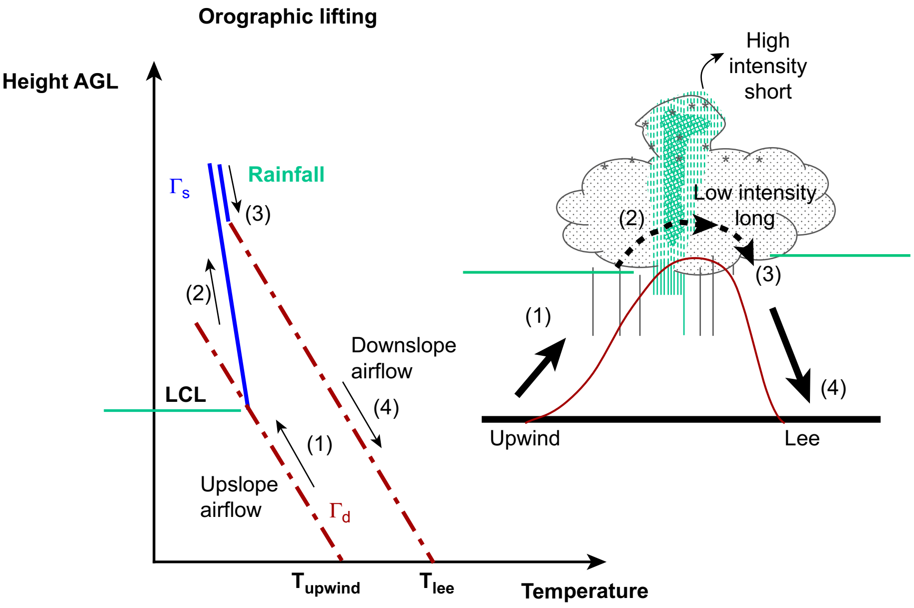
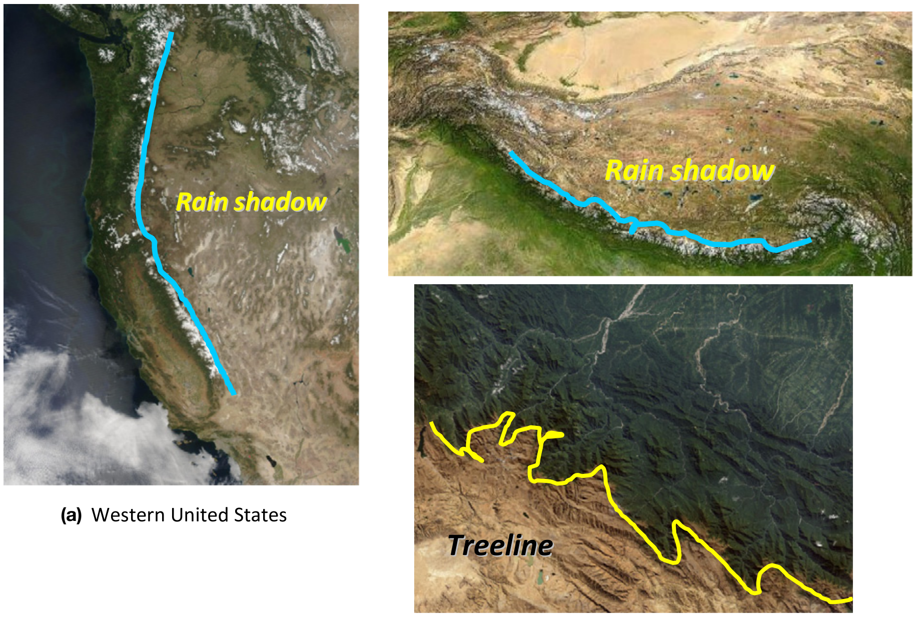


Figure 1 Conceptual representation of orographic precipitation processes. Colder and moist upwind air is forced to rise (1) until it reaches the lifting condensation level (LCL); it then becomes saturated, leading to the development of an orographic cloud, and with time, rainfall (2). As saturated air moves over the mountain (3), it eventually leaves the cloud and flows downslope on the leeside (4). If there is instability, localized convection can be triggered, leading to high-intensity precipitation. (T, temperature; Γ, lapse rate; subscript: d, dry adiabat; s, saturated adiabat).

transport) of topographic divides downwind of major mountain barriers, such as the Andean and Tibetan Plateaus, and the Sierra Nevada mountains in California (e.g., the Death Valley) (e.g., Barros and Lettenmaier 1994). At very high elevations and low temperatures, the saturation vapor pressure in the atmosphere (sometimes referred to as the moisture-holding capacity of the atmosphere) is smaller, and consequently, even if clouds form the cloud droplet concentration is too small to produce precipitation. Thus, typically, there is an orographic precipitation maximum on the slopes at some distance upwind of the mountain crest (Figure 1). At low elevations, leeside rain shadows can be explained by drier (due to upwind depletion) and warmer air flowing downslope. Although this classical description of the spatial and altitudinal contrasts of precipitation across topographic features is consistent with the broad landscape-scale evidence of vegetation contrasts (Figure 2), quantifying orographic precipitation generally and quantifying it at the spatial and temporal scales that reflect governing key meteorological, hydrological, and ecological processes requires high spatial and temporal resolution observations and models that can capture the complexity of precipitation processes including the diurnal and seasonal cycles and interannual variability. One major challenge in assessing climate impacts and climate vulnerabilities at local places, and at the scales of headwater catchments in mountainous regions in particular, is the fact that Global Climate Model (GCM)-based predictions and integrated assessments such as those produced by the Intergovernmental Panel on Climate Change (IPCC) are available at very coarse spatial scales, and confidence in GCMs' ability to capture present climate processes at regional and smaller scales in the lower troposphere is very limited. For example, even in the case of reanalysis data sets obtained by optimal assimilation of model results and observations over the recent historical record (typically about 50–60 years), there is significant discrepancy between the statistics of extremes as compared to rainfall observations (e.g., Sun and Barros 2009). Nevertheless, these scenarios have been used to provide baseline information for constructing a subset of alternative vulnerability scenarios, which are then constrained locally (e.g., Bates et al. 2008; Vörösmarty et al. 2010).

Figure 3 shows the annual cycle of river discharge from mountain streamgauges randomly selected among headwater catchments of some of the world's largest river basins in the University of New Hampshire-Global Runoff Data Center Composite Runoff Fields Version 1.0 (http://www.grdc.sr.unh.edu). The two top panels illustrate the difference between two headwater catchments (of different sizes) on the eastern slopes of the Andes, although at different latitudes. The data on the left-hand panel shows only the signal of the South American monsoon (JFM, January, February, and March) for a tributary of the Parana river, whereas the right-hand panel shows also a strong signal in the Austral spring (OND, October, November, and December) for a tributary of the Amazon, reflecting the relative contribution of large-scale moisture transport (JFM) versus regional and local sources (OND) that can amount up to 30–35 mm in the annual cycle of precipitable water (Figure 4). Both regional and synoptic-scale moisture sources are susceptible to change if the regional climate warms. Rainfall intensity increases in December, January, and February (DJF) and decreases in June, July, and August (JJA) at both the Andes locations, along with significant increases in precipitation intensity and number of dry days (Bates et al. 2008). That is, the wet season would become wetter with more intense rainfall events, whereas the winter season would become very dry. This is consistent with regional drying of the lower troposphere as rainfall intensity in the winter is



(b) Himalaya and Tibetan Plateau

(a) Western United States

(c) Bolivia, Andes

Figure 2 Visible satellite imagery of rainfall deficit on the leeside of mountain regions (rain shadow): (a) The rain shadow on the eastern slopes of the Cascades and the Sierra Nevada mountains from Washington State to Southern California; (b) The rain shadow of the Himalayas is the Tibetan Plateau. In the figure, the rain shadow is to the right of the blue line that follows the Cascade mountains and the Sierra Nevada, and to the north of the blue line that matches the topographic divide in the Himalayas. In the case of very high mountains, such as the Himalayas and the Andes, the rainfall peaks below the topographic divide, establishing a clear tree line on the upwind slopes as shown in (c) on the eastern slopes of the Andes in Bolivia. Source: www.earthobservatory.nasa.gov.

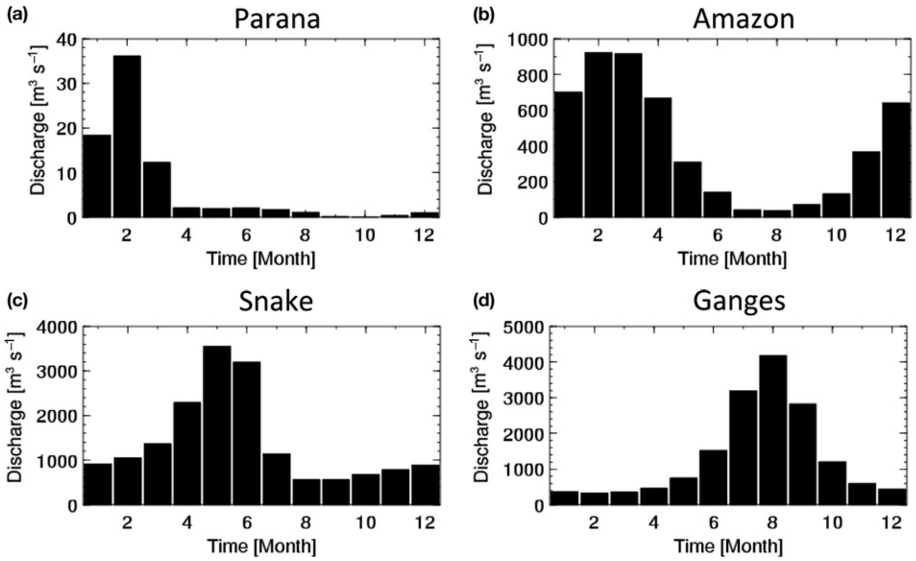


Figure 3 Annual cycle of river discharge for four mountain catchments at the headwaters of the major river basins indicated in each graph: (a) Parana, (b) Amazon, (c) Snake, and (d) Ganges. Source: University of New Hampshire-Global Runoff Data Center Composite Runoff Fields Version 1.0 [Available online at http://www.grdc.sr.unh.edu].

very low and is strongly controlled by local moisture sources and fog–stratus interactions. The bottom row in Figure 3 shows the annual cycle of streamflow for two stations in the northern hemisphere: one in the Snake River (left-hand side), a tributary of the Columbia river originating in the Rocky Mountain in North America, and a tributary of the Ganges in the southern slopes of the Himalayas in the Indian subcontinent (right-hand side). The streamflow of the former is dominated by snowmelt

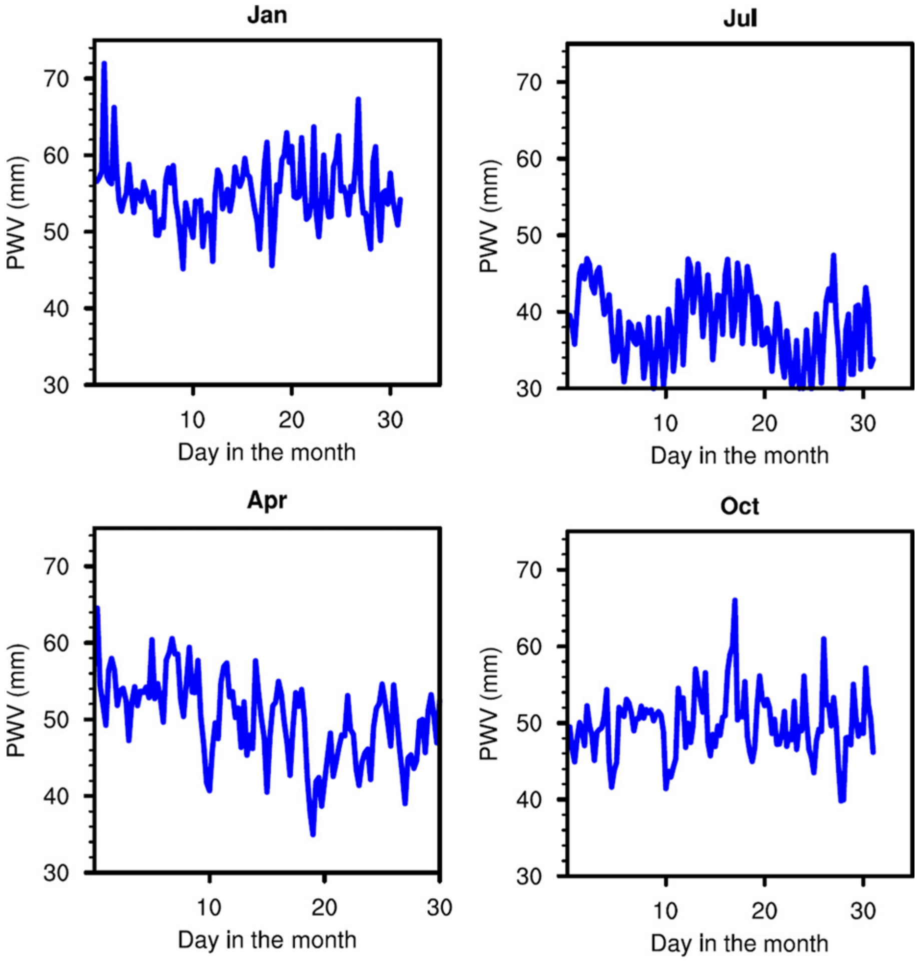


Figure 4 Day-to-day variability of precipitable water (PWV) from the ERA data set (European Center for Medium term Weather Forecasting (ECMWF) Reanalysis ERA) over the Kospiñata river valley in the Central Andes for four different months in 2011: January – wet season; July – dry season. Source: ERA-Interim data-portal.ecmwf.int/data/d/interim_daily.

runoff in the spring; the streamflow in the latter is dominated by summer monsoon runoff. For the Snake river basin, there is large uncertainty in simulated climate change projections; however, most model results suggest changes in timing of snowmelt (earlier in the year) and increases in evapotranspiration (ET) leading to lower soil moisture overall, and therefore a likely shift in the seasonality of the streamflow peak (Bates et al. 2008). In the case of the Indian monsoon, global model simulations of climatic change scenarios point to a significant increase (10–20%) in runoff associated with increased rainfall intensity during the monsoon (Bates et al. 2008). However, a significant increase in the number of dry days over the Indian subcontinent, and over the Gangetic Plains in particular, could counteract any benefits from increased infiltration and runoff production, leading to essentially no change in groundwater recharge regionally.

Large regional variability in the vulnerabilities of mountainous regions to climate coupled with differences in governing precipitation processes at different locations implies the need for climate vulnerability assessments and adaptation studies that are based on an understanding of the governing hydrometeorological processes at regional scales and provides an impetus to the case that development of long-term observing networks in mountainous regions is foundational for devising climate mitigation and adaptation strategies in mountainous regions. The idea that climatic observations are essential to address environmental change and sustainability questions is not new (e.g., Plummer et al. 2003). Yet, mountains remain generally among the least observed landscapes in the planet (e.g., Viviroli et al. 2011). For example, the first above-canopy, science-grade rainfall observing network in the eastern slopes of the Andes from the Amazon basin up to the top of Parque Nacional del Manu was installed only recently, in the Fall of 2011 (Figure 5). As opposed to what happens in the eastern slopes of the central Andes where rainfall peaks in the early afternoon, rainfall peaks in the evening and early morning in the south-facing slopes of the central Himalayas (Figures 5 and 6). On the one hand, daytime ET plays an important role in modulating soil moisture and consequently surface–subsurface interactions and groundwater recharge; on the other hand, moisture recycling by ET at the ridge-valley scale can provide the supply needed to explain the observed diurnal cycle of precipitation when the regional moisture flux is insufficient (Bushan and Barros 2007). We hypothesize that

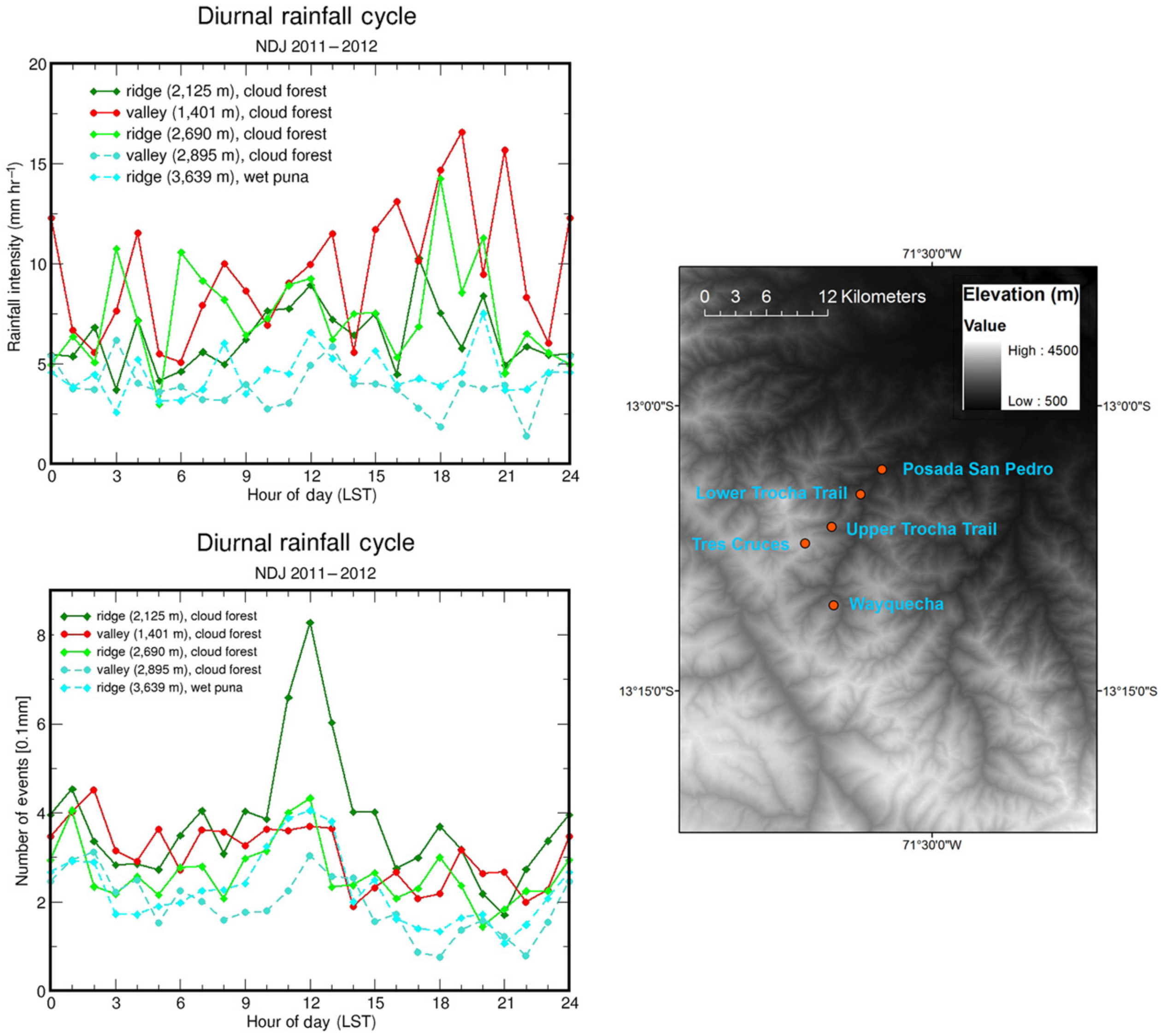


Figure 5 Characteristics of the diurnal cycle of rainfall at rain gauges in the Central Andes during the South American monsoon in 2011–12. Events are defined based on the daily average number of records of 0.1 mm h^{-1}. The diurnal cycle of rainfall intensity correspond to average values of recorded rainfall intensity at the specific time of day when rainfall occurred.

daytime ET in the central Andes is important to provide moisture supply for midafternoon upslope dense fog and low stratus that produce light rainfall at valley headwaters, whereas in the Himalayas it provides the moisture supply for afternoon cumulus convective activity (see further discussion in Section 504.01.2).

Published estimates of the contribution of orographic precipitation to global freshwater resource stocks vary from values greater than 70% in the snow-dominated hydrologic regimes of the western United States (e.g., Bales et al. 2006) to 25% in humid climates and 45–50% in arid and semiarid regions (Viviroli et al. 2011). However, even in regions where mountain freshwater per se is not essential for the sustainability of adjacent lowlands, precipitation patterns and associated runoff generation and erosion processes are critical in landscape evolution and in sustaining the incoming material fluxes (sediment, debris, and nutrients) that are essential for the sustainability of floodplains and river systems at low elevations (e.g., the eastern Andes and the Amazon basin, McLain and Neiman 2008).

5.04.2 Landform and Orographic Precipitation Regimes

Classical measurements of precipitation date back centuries and consist of cumulative rainfall amounts (direct observations) over predetermined durations (e.g., 1 day, 1 month) at point locations. Remote and difficult access severely increases the costs of installation and maintenance of precipitation networks in mountainous regions. A fundamental shift in the measurement paradigm took place with the advent of the

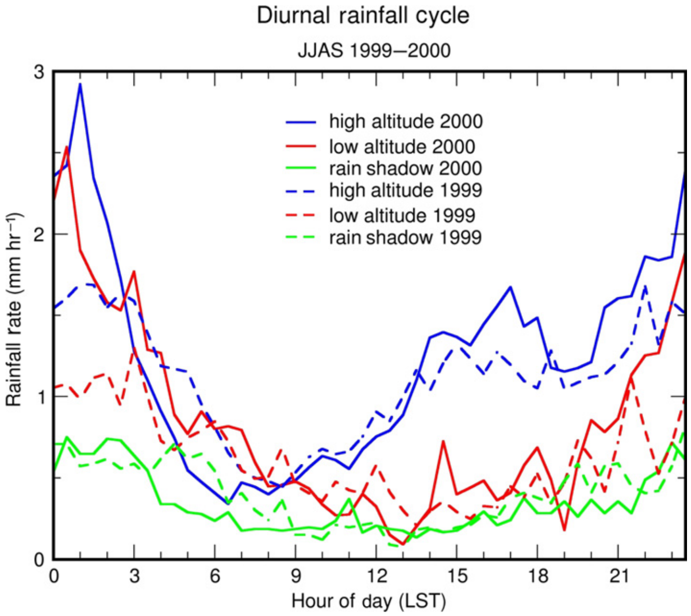


Figure 6 Diurnal cycle of monsoon rainfall in the Central Himalayas at high (ridges) altitude and low altitude (valleys) and rain shadow locations in the Marsyangdi river valley in 1999 and 2000. The rainfall rate is calculated including also times when it was not raining; it is not a rainfall intensity. Adapted from Lang and Barros 2002; Barros et al. 2000.

satellite era in 1978 and the launch of the first microwave and infrared imagers, the popularization of ground-based radars in the late 1980s and 1990s, and finally the Tropical Rainfall Measurement Mission (TRMM) satellite with the first precipitation radar in space; that is, clouds and precipitation fields can now be mapped globally at increasingly high spatial and temporal resolution over time (Adler et al. 2000; Negri et al. 2002, 1994 among others; see Chapter 5.9 on rain measuring satellites). The panoramic view of clouds and precipitation systems afforded by remote sensing reveals the complex spatial gradients of transient cloud and rainfall fields, the nonlinear and often apparently chaotic evolution of storm systems on the one hand, and the remarkable space–time organization imposed by landform on the same fields on the other hand. However, experience has demonstrated that until science-grade observing systems are put in place, precipitation in mountainous regions tends to be underestimated based on operational ground-based networks and satellite data by as much as 300% and higher (e.g., Barros et al. 2000), and the characteristics of rainfall (seasonal and diurnal cycles, duration and intensity of specific events) and spatial gradients that in turn strongly determine its availability as a resource are poorly described (Figure 7).

5.04.2.1 Rainfall

Precipitation in continental monsoon climates in the tropics is characterized by strong annual cycles, with most of the precipitation falling during the warm season: JJA in the northern hemisphere and DJF in the southern hemisphere. From onset to demise of the monsoon, large-scale atmospheric circulations sustain the bulk influx of moisture to mountainous regions. However, the physical processes by which the complex spatial and temporal patterns of precipitation observed from the ridge-valley scale to the mountain-range scale unfold are poorly understood. In the past 10 years, analysis of space-borne observations of clouds and precipitation systems revealed unique features in the spatial organization of rainfall and cloudiness in mountains (the Himalayas and the Andes in particular) that suggest strong landform controls on precipitation processes (Garreaud 1999; Garreaud and Wallace 1997; Barros et al. 2004 among others). Specifically, analysis of TRMM PR (Precipitation Radar) and infrared imagery data along the Himalayas suggests orographic precipitation processes that include cells of localized shallow convection embedded in bands of stratiform rainfall from the foothills up to 5000 m (Lang and Barros 2002; Barros et al. 2004). For example, Barros et al. (2004) and Giovannettone and Barros (2008, 2009) showed that the first principal component of cloudiness in the Himalayas and the Andes explained 50–70% of all variability (Figure 8), and they also showed space–time persistence on the distribution of precipitation features (Figure 9). This clear and strong modulation of clouds and precipitation fields by mountains viewed from space can be explained by their strong 3D complex morphology, which at a regional scale performs like an obstacle to synoptic-scale flow and as an elevated heat source with a diurnal cycle governed by solar forcing. At the ridge-valley scale and across topographic barriers modulation of flows by topography, spatial organization of convective activity, and diurnal mountain-plain and ridge-valley circulations organize aerosol distributions, which play an important role as cloud condensation nuclei (CCN), clouds, and ultimately precipitation processes (e.g., Shrestha and Barros 2010; Brun et al. 2011).

Figure 10 summarizes various habits of orographic clouds and precipitation including (1) rainfall associated with large-scale weather systems: stratiform rainfall associated with large-scale weather; stratiform rainfall with shallow embedded

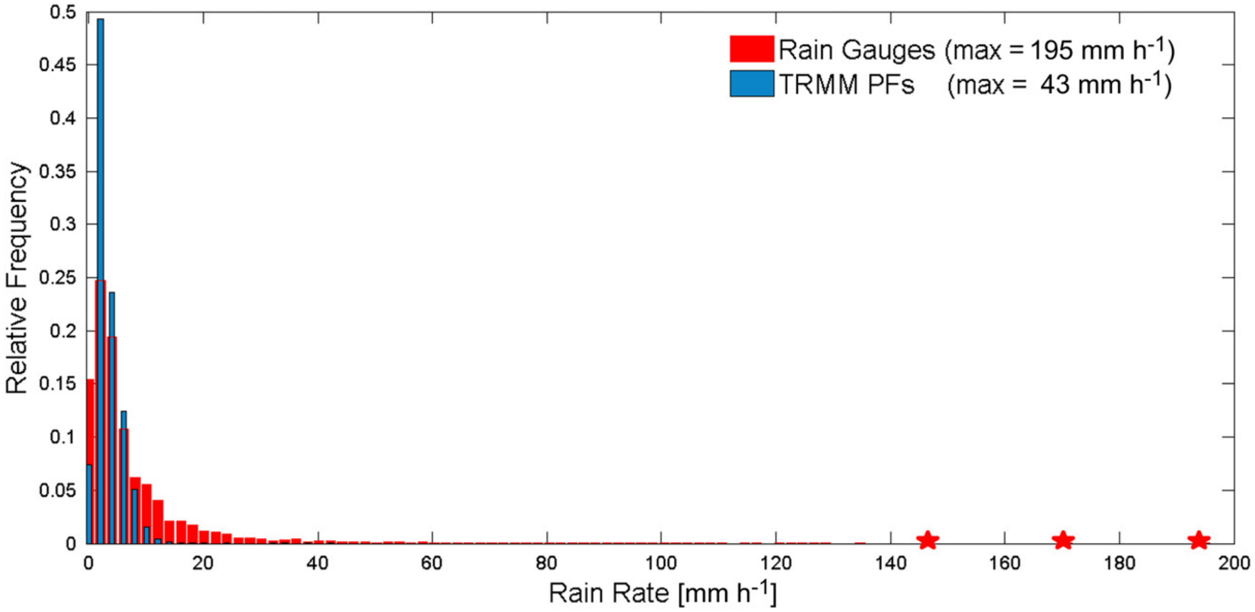


Figure 7 Intercomparison of the histograms of rainfall rates (resolution is 2 mm h^{-1}) based on 12 years of TRMM precipitation features in a region centered over the Kospiñata valley and recent observations ($<$1 year) from five rain gauges. Three highest observed rainfall intensities are marked with red stars. Although the period of record is very different, the objective of this figure is to illustrate the differences in the range of observed rainfall. The histograms show that the satellite misses light rainfall ($\leq$2 mm h^{-1}) and underestimates higher rainfall intensities. Precipitation features courtesy of Chuntao Liu. Precipitation features climatology after Liu et al. 2008.

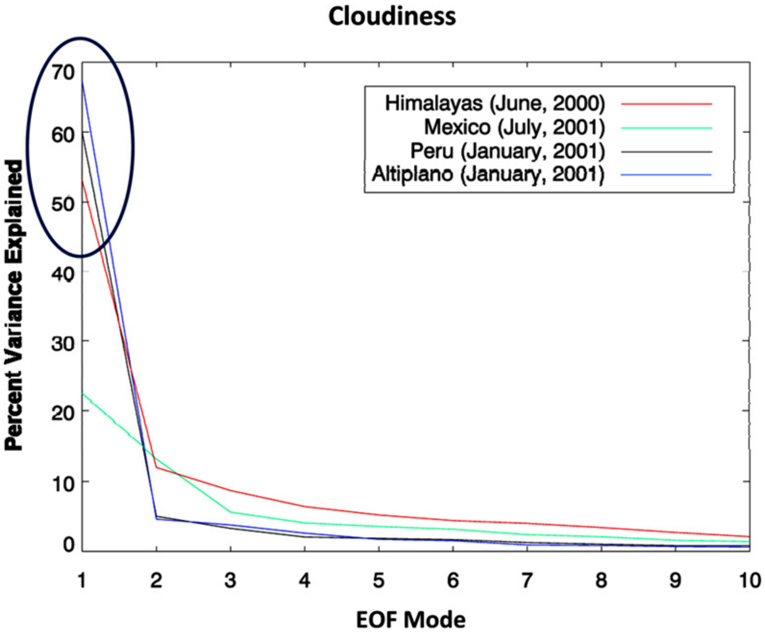


Figure 8 Empirical orthogonal function (EOF) analysis of infrared brightness temperature as an indicator of cloudiness over the Himalayan range, the Sierra Madre Cordillera in Mexico, the Central Andes in Peru, and the Altiplano region in the Andes. Adapted from Giovannettonne and Barros (2009).

convection, which dominates the occurrence of heavy localized nocturnal rainfall in the Andes and the Himalayas; and stratiform rainfall with embedded deep convection associated with the propagation of mesoscale convective systems such as in the warm season in the Southern Appalachians and (2) rainfall associated with the interaction between large-scale weather and local circulations: rainfall resulting from feeder–seeder interactions between stratiform clouds and low-level orographic clouds during midday and between low-level clouds and fog (advection fog in the morning, upslope fog in the late

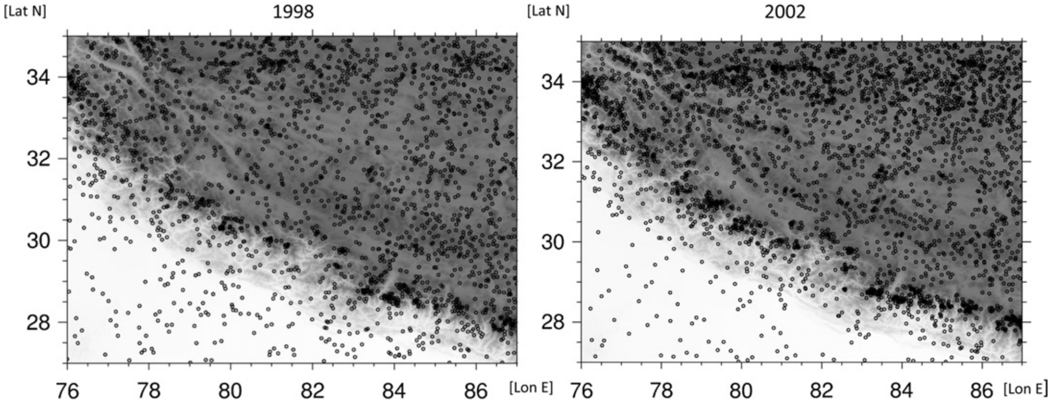


Figure 9 Examples of interannual persistence of TRMM warm rainfall features (Nesbitt and Zipser 2003) locked to ridges along the Himalayan range and high elevation features in the Tibetan Plateau. Adapted from Barros et al. (2004).

afternoon, and radiation fog in the early evening), shallow cumulus convection associated with local ridge-valley circulations, and isolated deep convection associated with thunderstorms (evening, midnight, and early morning). For further in-depth discussion of the dynamics of orographic precipitation systems see Houze (2003, 2012). Note that consequent to the 3D space–time organization of clouds and precipitation, there is a corresponding spatial and temporal organization of air and land surface temperature, net radiation, soil moisture, boundary layer relative humidity, and ET, that is, the conjugated water and energy budgets.

At a macroscale level, some fundamental differences in rainfall relate to seasonal climatic variations (e.g., monsoon systems), diurnal cycle, rainfall intensity (light versus heavy – $>10\,\mathrm{mm\ h^{-1}}$), and rainfall duration (typically, long for light rainfall and short for extreme rainfall). Previous research in the Himalayas, Central America, and the Central Andes using TRMM radar data (Giovannettone and Barros 2008, 2009; Barros et al. 2004) showed that orographic convective rainfall systems exhibit a strong diurnal cycle that is strongly organized by topography with deep and shallow ($<5\,\mathrm{km}$) convective systems aligned with ridges and elevated features during the daytime and moving downslope at night along the ridges of valleys opening to the adjacent plains (Figure 11). The diurnal cycle of rainfall in the central Himalayas exhibits afternoon and evening peaks with nocturnal maxima during the monsoon (Barros et al. 2000; Barros and Lang 2003). This late night/early morning rainfall maximum accounts for about one-third of the cumulative monsoon rainfall and causes regular flash floods in headwater streams everywhere along the Himalayan range.

One interesting feature of Andes' hydroclimatology is the alternation of wet and dry spells similar to active and break phases of the monsoon in the Himalayas (e.g., Nogues-Peagle et al. 1997; Chapter 5.14 deals with Andes snowpack). Previously, analysis of the diurnal cycle of convective rainfall in South America during the monsoon season (DJF), and specifically along the steep terrain in the eastern slopes of the Central Andes, also reported a strong diurnal cycle with an evening peak and nocturnal maxima along the foothills of interior valleys (Negri et al. 1994, 2002; Garreaud 1999, Garreaud and Wallace 1997; Yang and Slingo 2001; Mapes et al. 2003; Okumura et al. 2003; Nesbitt and Zipser 2003). However, recent observations from the Kospiñata river basin suggest that in contrast to the Himalayas, the evening rainfall peak occurs at lower elevations and in the valleys in the Andes (Figure 5). Heavy, localized nocturnal rainfall at lower elevations is the leading cause of powerful flash floods, causing myriad landslides and debris flows at elevations below 3000 m, illustrated by the sharp transitions in the hypsometric curves of these regions (e.g., Figure 12). Daytime rainfall on the ridges peaks in the early afternoon (noon–3 p.m. local standard time (LST)) followed by another rainfall peak in the evening, maintaining wetness of the soil during the rainy season and thus making it less stable.

A critical challenge to rainfall estimation from satellites is the detection of light rainfall. In addition, terrain effects in mountainous regions also play an important role in limiting the accuracy of precipitation estimates (Barros et al. 2000; Barros and Tao 2008; Prat and Barros 2010a,b). There is therefore a great need for ground-based observations in order to quantify total rainfall and to fully characterize the diurnal cycle. Persistent fog (drop size $<50\,\mu\mathrm{m}$; Eldridge 1961; Awan et al. 2011, among others) and light rainfall are not main features in the central Himalayas during the monsoon, whereas this is not the case in the Andes (Figure 5), Central America, Coastal Range of Southern California and Southern Appalachians, and Hawaii (e.g., Gomez-Peralta et al. 2008; Juvik and Nullet 1995). Indeed, recent multiyear observations in the Southern Appalachians suggest that relatively light rainfall dominates net annual precipitation. Figure 13 shows the fraction of rainfall that is contributed by light rainfall ($<3\,\mathrm{mm\ h^{-1}}$) in the Great Smoky Mountains in North Carolina, which varies between 30 and 40% for annual rainfall and goes up to 60% and higher in winter and spring. Interannual variability of rainfall is very large, with rainfall on the eastern slopes varying by as much 1 m of net precipitation between dry and wet years. Note that the threshold criterion of $3\,\mathrm{mm\,h^{-1}}$ is applied to near-instantaneous measurements, and there are no spurious smoothing effects due to temporal integration. The difference between dry and wet years is in the occurrence of heavier rainfall associated with convective events (not shown).

Rainfall intensity as a discriminant of rainfall regime is critical for assessing the sustainability of freshwater resources in mountainous regions. For instance, if temperature changes, the

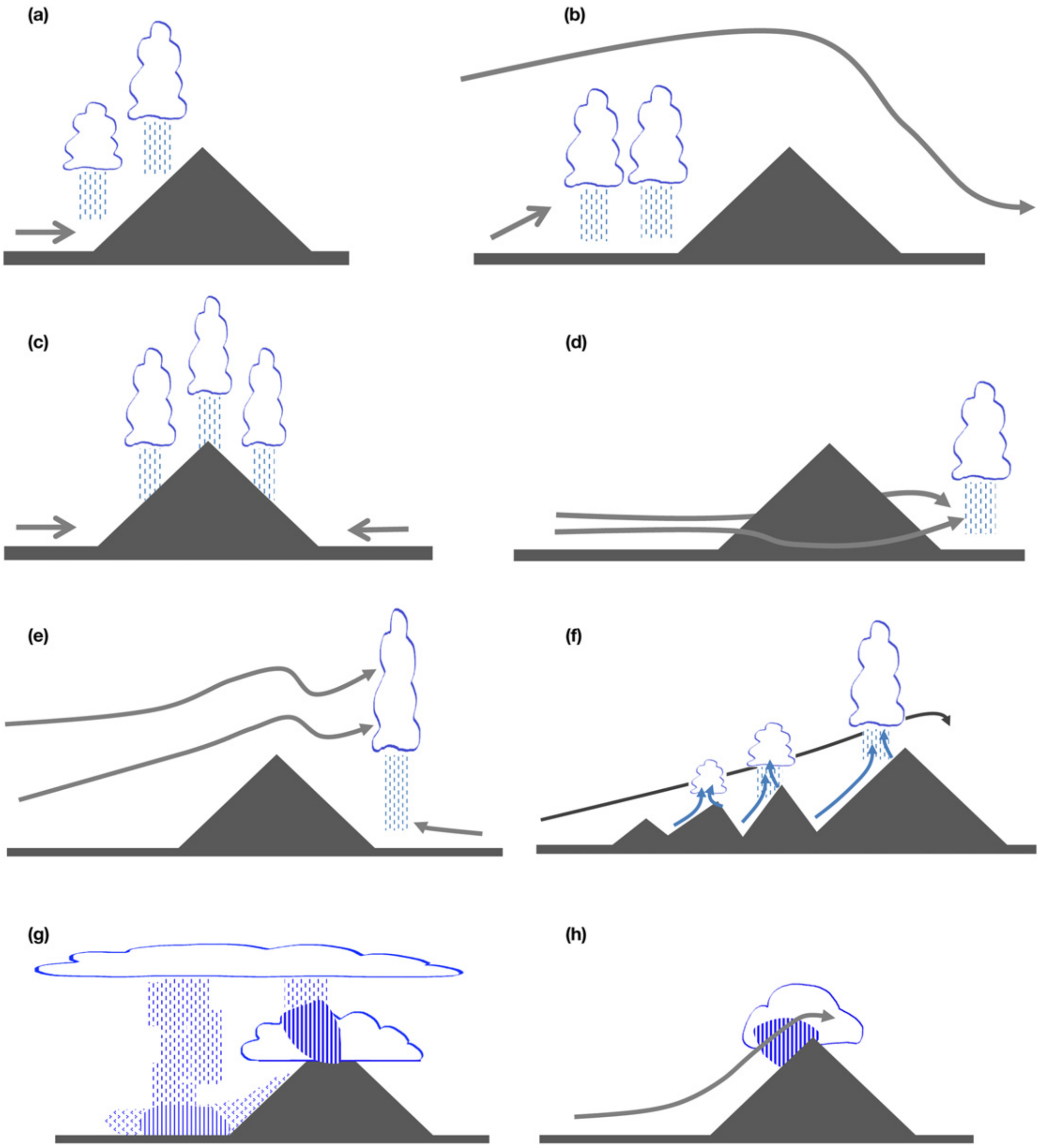


Figure 10 (a) Upslope triggering of convection; (b) upstream triggering of convection; (c) thermal triggering of convection; (d) leeside triggering of convection; (e) leeside enhancement of convection; (f) organization of upslope and leeside triggering and enhancement of convection by complex terrain; (g) feeder–seeder enhancement of rainfall – upstream and upslope enhancement of stratiform rainfall by deep fog and low-level orographic clouds; (e) upstream condensation and stationary deep orographic cloud. Modified after Fig. 12.24 in Houze (1993).

impact depends on how this would be reflected in the diurnal cycles of temperature. Morning light rainfall could be more sustainable than afternoon light rainfall, although light rainfall generally would be expected to decrease because of changes in fog and low-level cloud regimes, lower relative humidity, and increased low-level temperatures in the troposphere. Warm season light rainfall in dry years would be highly susceptible to evaporation. Changes in fog and rainfall intensity affect canopy harvesting of fog and interception of rainfall on the one hand and infiltration and soil moisture on the other. Lower surface soil moisture leads to increased soil and boundary layer temperatures, in a positive feedback loop, which would tend to further increase surface layer temperatures and the dryness of upper soil layers, thus affecting understory and forest floor vegetation at first, and consequently albedo, surface roughness, and depending on drought duration and overall environmental conditions, increasingly depleting soil layers where the deep-rooted canopy systems seek water, ultimately altering system-wide runoff production mechanisms in the soil saturated and unsaturated zones.

5.04.2.2 Snow

Because of complex thermodynamics, mixed-phase physics, and land–atmosphere interactions at the snow–air interface including wind redistribution, the spatial and temporal distribution of snow depth, snow temperature, structure, and snow water equivalent (SWE) are highly heterogeneous and widely

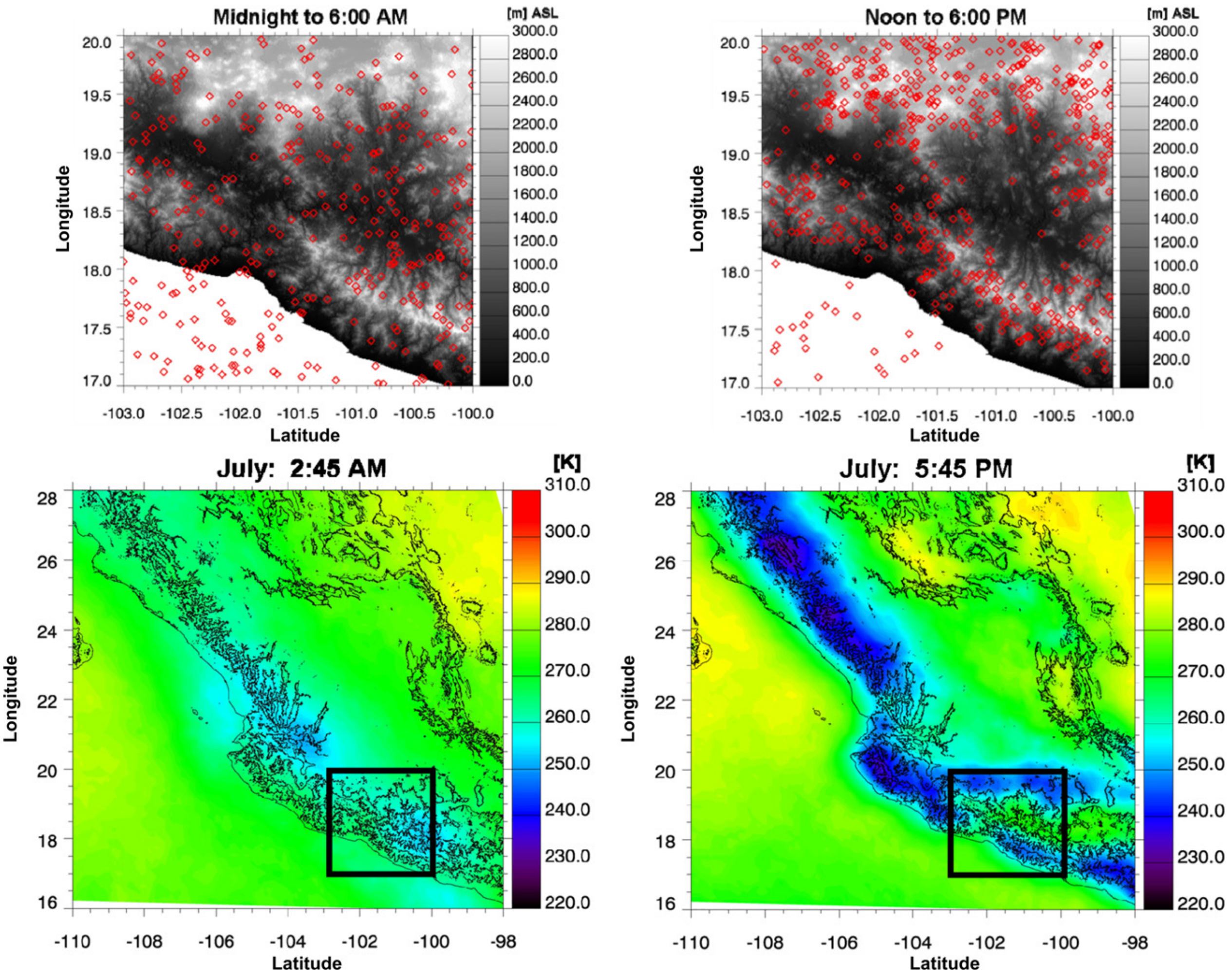

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Figure 11 Diurnal variation of cloudiness (bottom panels) and convective precipitation activity (top panels), respectively, from GOES infrared imagery and TRMM data Central America (Mexico, Sierra Madre Occidental). Adapted from Giovannettonne and Barros (2008).

variable in space and time, with very large changes over very small distances. Changes in SWE on the order of 100–300% are not unusual over small distances (tens to hundreds of meters) because of changes in landform, land cover, terrain aspect and insolation, and wind patterns (e.g., Cagnati et al. 2004; Sturm et al. 1995; among others). Traditional measurements that involve coring, digging, or extraction of snow samples are destructive in nature and thus modify snowpack structure on the one hand and are so labor intensive that they cannot be used to sample at the high resolution necessary to characterize the spatiotemporal variability of the snowpack, especially during ripening and melting seasons. Although expensive to install and with high maintenance costs, SNOTEL stations (SNOwpack TELemetry) provide the most rigorous ground-based measurements of SWE based on the weight of accumulated snow (snow pillow) as a function of time [http://www.wcc.nrcs.usda.gov/snow]. There are near 700 SNOTEL sites in the western United States, but the area covered is very large and the stations are very far from each other, thus essentially isolated point measurements. In addition, there are large uncertainties in the measurement due to heterogeneity of snow distribution and internal structure (grain-size distribution, ice layers, etc.) in the snow pillow itself. Other sensors such as cable time-domain reflectometry (TDR) can be installed semi-permanently from the beginning of the snow accumulation season, and thus can monitor the temporal evolution of the snowpack without affecting it. Flat cable TDR applications have been successful over distances up to 100 m (Waldner et al. 2001). The shortcoming is that TDR provides measurements only on the cable direction and along cable length, and therefore measurements over large areas and over rugged and remote terrain are effectively precluded for practical reasons.

Recently, a number of studies have been pursued in the application of ground-penetrating radar (e.g., Granlund et al. 2009). However, snow wetness is especially critical as small changes in volumetric liquid water content can lead to large errors in SWE estimates (e.g., Lundberg and Thunehed 2000). The great opportunity afforded by satellite-based observations is that they provide field estimates at a nominal scale of measurement (e.g., 0.25° × 0.25° MODIS resolution, the Moderate Resolution Imaging Spectroradiometer onboard the Terra and Aqua satellites). On the other hand, SWE errors up to

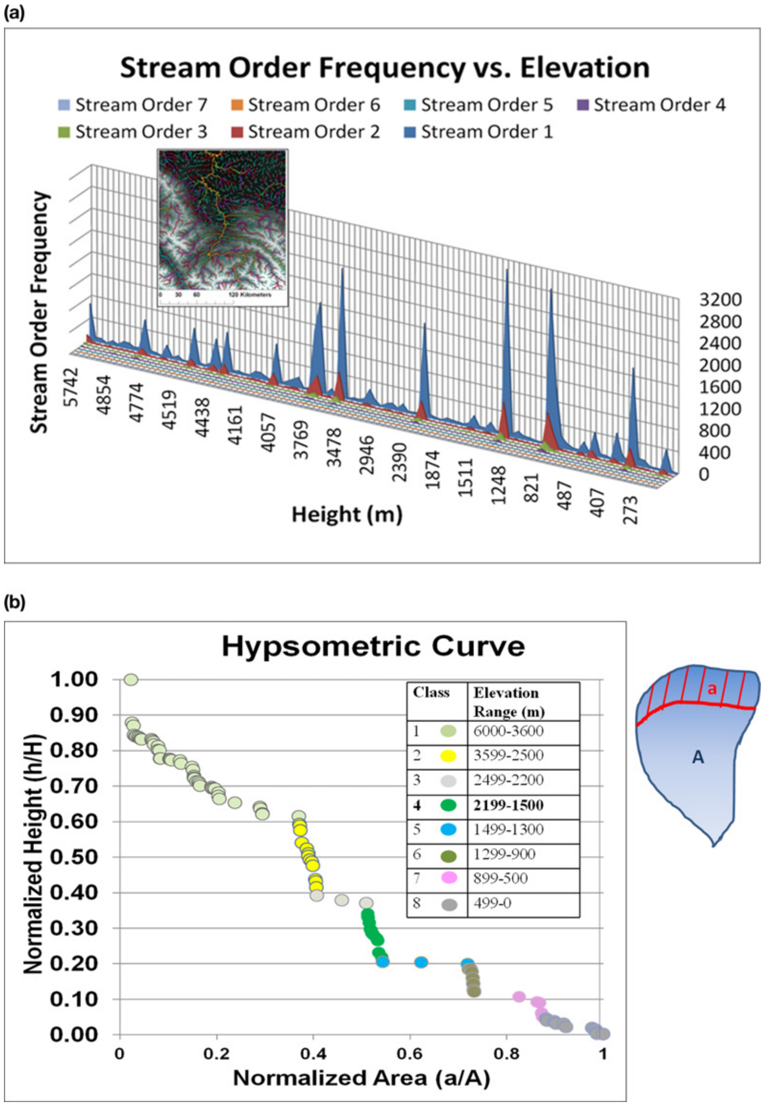

Figure 12 Geomorphic analysis of a digital elevation model (DEM) of the Kospiñata river valley spanning 10.75°–14.65° S and 69°–65° W on the eastern slopes of the Andes: (a) histogram of stream order frequency distribution with terrain elevation (inset is at the center of the DEM analyzed); (b) hypsometric curve describing the distribution of catchment area as a function of elevation from the divide toward the outlet (A, catchment area; a, catchment area above elevation h; H, maximum elevation within catchment).

50% at local places are common because of subgrid-scale variability (snow grain-size distribution, fingering effects and ice layers, wind redistribution, etc., within the satellite sensor footprint) that is not accounted for in operational retrieval algorithms (e.g., Foster et al. 2005; Kang and Barros 2011a,b). To characterize the subgrid-scale variability of snow properties as a function of water content and how that affects the radiometric behavior of snow and ice surfaces is therefore a critical research imperative for systematic remote sensing of snow from space (see, e.g., the recommendations of the Earth Sciences Decadal Survey conducted under the auspices of the Space Studies Board of the National Research Council (NRC 2007)). A distributed system of ground-based autonomous sensors operating at high spatial resolution should provide valuable information to characterize the subgrid-scale variability of the properties of seasonal snowpacks as a function of time, which then could be integrated into retrieval algorithms (Kang and Barros 2010).

5.04.3 Coupled Land–Atmosphere Interactions and Mountain Ecohydrosystems

We take the blue and green water framework (Falkenmark and Rockström 2006; see their Figure 1), where blue water encompasses both surface runoff water and groundwater to address the question of water resources and sustainable ecosystems in mountainous regions. Recent modeling studies of the diurnal cycle of rainfall in mountainous regions around the world (e.g., Iwasaki 2003: Japan; Pistotnik and Haiden 2004: European Alps; Yang et al. 2004: Tibetan Plateau; Bushan and Barros 2007: Sierra Madre in Mexico) suggest that ET and

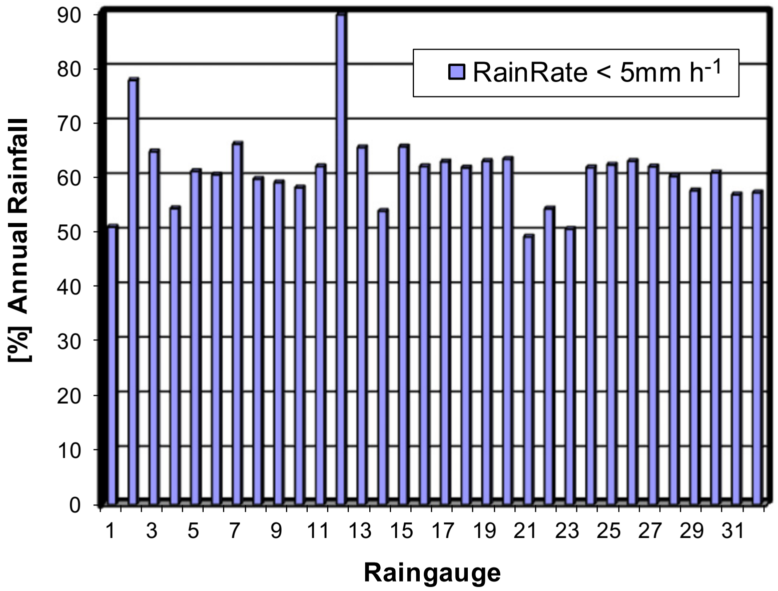

Figure 13 Light rainfall ($<5\,\mathrm{mm\,h^{-1}}$) 2008–11 in the Great Smoky Mountains expressed as a fraction of the total annual accumulation.

mountain–valley moist transport have a strong influence in the diurnal cycle of precipitable water (PW) and convective available potential energy (CAPE), thus ultimately affecting the location and timing of the onset of convection in daytime, and establishing conditions for late evening convective activity. While such studies have been conducted for different synoptic environments and moderate topography (500–1500 m elevation differences), we also found that the diurnal cycle of rainfall in the Himalayas exhibits similar features, including a nocturnal maximum that follows concurrent local maxima in PW and CAPE independently of the strength of monsoon forcing (Figure 14; Lang and Barros 2002; Barros and Lang 2003). This suggests the ubiquity of a dynamic link between topography, the spatial variability of ET (and soil moisture) via surface sensible and latent heat fluxes, and the spatial organization of rainfall by which the mountains modulate precipitation processes (Monteith 1995; Pielke 2001). Interactions between land cover and cloudiness are well known from satellite data (O'Neal 1996; Rabin and Martin 1996; Wielicki et al. 1993). The observed collocation of the spatial patterns of the diurnal cycle of cloudiness and orographic precipitation with specific terrain features and land cover patches in the tropics provides strong physical evidence to the hypothesis (1) that landform, land-cover patterns, soil moisture, clouds, and precipitation are dynamically interconnected on steep altitudinal gradients and (2) that ET plays a key role in the spatial organization of precipitation at the ridge-valley scale, even in the presence of strong monsoon (large-scale) forcing (Foster 2001; Barros et al. 2004, 2006). In the eastern slopes of the Central Andes, we hypothesize that interactions among moisture advection from the Amazon basin at lower elevations and upslope fog at higher elevations and cumulus clouds organized by ridge-valley circulations explain the persistent rainfall throughout the day at all elevations, albeit with strong decreases in rainfall intensity with elevation.

In the absence of synoptic forcing, orographic precipitation data typically show an afternoon peak over ridges associated with diurnally forced upslope flow. While such a peak is visible in the Himalayan data (Barros et al. 2000), its relative contribution to the observed monsoon rainfall is small in the region, especially at low elevations and in the valleys (Barros et al. 2000, 2004). Instead, Barros et al. (2000) noted a nocturnal peak in rainfall, just past midnight. Other researchers have noted this regional phenomenon as well (Ueno et al. 2001), and we also find it in the Andes. On the other hand, in the Central Andes, in the Amazon-Manu transect, the early afternoon rainfall peak based on preliminary data appears to account for up to 20–30% of all rainfall. One possible explanation for this difference is that the Amazon provides a sustained moisture source for the eastern slopes of the Andes, even in the absence of large-scale advection, whereas no such equivalent regional moisture source exists in the Himalayas. This finding motivated the Monsoon Himalaya Precipitation Experiment (MOHPREX; Barros and Lang 2003).

During MOHPREX, the diurnal evolution of thermodynamic conditions in the lower troposphere from radiosondes launched at Besisahar in the central Himalayas shows normal diurnal heating and cooling of the atmosphere, which is perhaps lagged a bit by the high moisture levels. Also, there is a daily replenishment of moisture occurring at all levels after the nocturnal depletion by rainfall. The timing of these two processes leads to the observed diurnal evolution of CAPE and PW (Figure 14). The net daily depletion of atmospheric moisture was estimated as ~6 mm on average (Barros and Lang 2003). This moisture supply must be restored daily through local ET and through large-scale advection. ET estimates varied between 0.5 and 6 mm per day, corresponding to an average daily evaporative fraction (ET/rainfall) on the order of 0.15. At lower elevations, which do not see rainfall during the day, the evaporative fraction corresponds to average premonsoon values of about 0.35 when soil moisture availability is not a limiting factor. Although spatially variable, the observations imply that 15–35% of the daily surface ET is locally or regionally recycled (Barros and Lang 2003). This is consistent

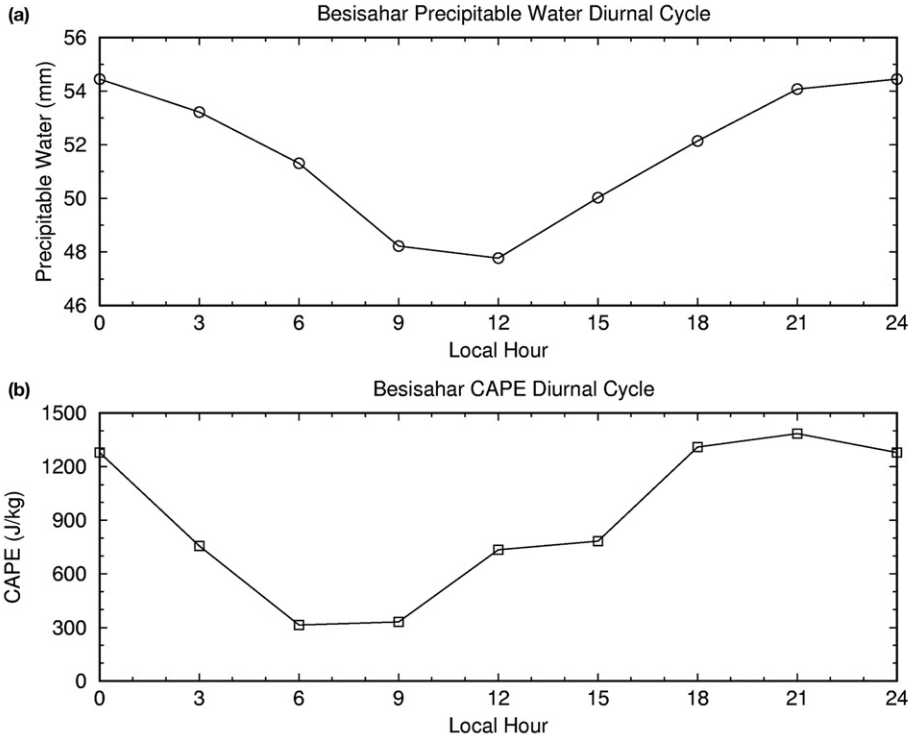

Figure 14 Diurnal cycle of (a) precipitable water (PW) and (b) convective available potential energy (CAPE) in central Nepal at Besisahar during MOHPREX (Monsoon Himalaya Precipitation Experiment). Adapted from Barros and Lang (2003).

with results by Iwasaki and Miki (2001), Iwasaki (2003), Pistotnik and Haiden (2004), and Bushan and Barros (2007), elsewhere who attributed a daytime increase in PW on the order of 2–5 mm associated with surface ET and mountain–valley circulations alone. Low-level moisture resulting from ET is advected upslope and up valley during daytime to increase the humidity in the mixed layer along ridges and at the headwaters of interior river valleys when large-scale moisture advection is absent or otherwise cannot penetrate because of blocking effects (Barros et al. 2006).

Pistotnik and Haiden (2004) investigated the effect of surface ET in the central parts of the Alps by switching off evaporation as a moisture source to the atmospheric boundary layer (ABL) in the numerical simulation of a storm case (LE was set to zero only where it represents a water source for the atmosphere, but nowhere else). In the unmodified simulation, convective precipitation starts in the late morning, around 09 UTC (Coordinated Universal Time), and is initially strictly tied to orographic features, where orographically induced convergence of the near-surface wind coincides with moisture advection. It takes two or three more hours until convection starts in the central parts of the Alps that are not in the path of moisture advection from adjacent basins or broad valleys. This scenario is very similar to our hypothesis about the role of moisture advection from the Amazon in the Central Andes. By contrast, in the experimental run without ET input, Pistotnik and Haiden found that cloud bases were significantly higher (by up to 1 km) than in the reference run. In the inner mountain areas, rainfall was completely absent, indicating that where large-scale moisture advection did not penetrate, surface ET was the essential humidity source. One interesting result of this study is the suggestion that progressive drying of the ABL during the day allows stronger daytime heating over the mountains and intensifies wind convergence over the ridges, eventually constraining precipitation to the locations where convection is favored and low-level moisture can be replenished by regional transport. Although these simulations were conducted in the context of numerical weather prediction without considering explicitly altitudinal gradients of vegetation, this behavior is consistent with the presence of the secondary afternoon peaks in rainfall, PW and CAPE at high elevations on the ridges in the Marsyangdi network in the Himalayas, and first observations in the Central Andes, and provides support for our hypothesis regarding the role of vegetation on the diurnal cycle of orographic clouds and rainfall, where ET from the elevations covered with rain forest may be a critical moisture supply to support late afternoon fog and cloud formation at high elevations in the cloud forest.

Yang et al. (2004) illustrate how evaporative cooling of rainfall may interact with mountain–valley circulations to affect deep convection using a 2D simulation in the Tibetan Plateau. Late morning or early afternoon convective rainfall on the ridges evaporates and cools the lower levels of the troposphere, and can force downslope flows that interact with the preexisting upslope flows to establish convergence away from the ridge, eventually triggering convective activity toward the valley. Solar heating and compensating subsidence over the ridges would then establish conditions to drive upslope flow again to the ridges, leading to the establishment of a ziz-zag pattern in the spatial distribution of rainfall from ridge to valley back to ridge. This mechanism might explain the 2–3 h lags in early evening rainfall between high and low elevation stations in the Marsyandi network when the synoptic-scale forcing is weaker (Barros et al. 2000; Barros and Lang 2003), and it is also found in the preliminary data from the Andes.

In the absence of large-scale moisture convergence, PW over the mountains should begin to decrease in the late afternoon and evening as surface latent heat fluxes progressively decrease and the atmosphere over the valley becomes colder and dry because of baroclinic compensation (Kimura and Kuwagata 1995). However, while ridge precipitation leads valley precipitation during the day and into the evening, this is not the case at nighttime. The nocturnal maximum over the ridges and against the orographic divide is observed either in sync with the nocturnal peak in the valley at low elevations (Bushan and Barros 2007), or 1–2 h later for strong and weak synoptic forcing conditions, respectively. Research toward clarification of these processes is needed.

5.04.4 Climate and Environmental Change Vulnerabilities of Mountainous Regions

5.04.4.1 Headwater Catchments and Water Resources

In mountainous regions, orographic processes control precipitation, and therefore, headwater streams are critical in capturing rainfall directly and through surface and surface runoff mechanisms to be delivered to valleys and reservoirs downstream at lower elevations. Because most rainfall tends to occur at specific places in the landscape according to regional hydroclimatology and topography (Barros et al. 2004), headwater catchments are also critical in terms of aquifer recharge in mountainous regions (Barros 2008). Headwater streams also provide important ecosystem services. For example, benthic macroinvertebrates in headwater streams are food for small mammals and for fish communities downstream, and also perform the important function of breaking down coarse organic matter, such as leaves and twigs, and releasing fine organic matter. When the benthic macroinvertebrate community is changed or extinguished in an area, even temporarily, as occurs during land use changes, it can have repercussions in many parts of both the terrestrial and the aquatic food web. Because there is little upstream or stream-to-stream migration of benthic macroinvertebrates, once headwater populations are eliminated, there is little hope for restoring a functioning aquatic community (Silsbee and Larson 1982). In addition to macroinvertebrates, these streams support diverse populations of plants and animals that face similar problems if streams are disturbed. In summary, headwater streams control flooding, recharge groundwater, maintain water quality, reduce downstream sedimentation, recycle nutrients, and create habitat for plants and animals.

Light rainfall defines, the regional background hydrometeorological regime in the Southern Appalachians and provides the baseline freshwater input into the regional natural hydrosystems, including the minimum water availability requirements for existing ecosystems. Here, we make the case that light rainfall is a lifeline process essential for the sustainability and resilience of mountain ecosystems first, and adjacent lowlands next (in the Piedmont of North Carolina average rainfall fraction also varies between 30 and 40% of the annual net, although there is a stronger seasonal effect, especially in the summer). Furthermore, the frequency of light rainfall peaks in the morning, especially in the summer and fall seasons when there is more frequent afternoon convection. Rain drop size distributions (DSD) obtained with microrain radar (MRR) profiles at different elevations suggest that morning light rainfall may be attributed to seeder–feeder interactions among valley fog, low-level orographic clouds, and regional stratus, whereas radiation fog likely plays an important ‘feeder’ role in the evening (Barros and Lettenmaier 1994; Prat and Barros 2010a). In the Andes, we hypothesize that upslope fog advection and blocking at elevations between the topographic divide support light afternoon rainfall above 3000 m.

Figure 15 shows examples of two 1-year long experimental simulations for a headwater catchment in the Great Smoky Mountains with and without light rainfall, everything else being the same. Note the reduction in cold season streamflow response overall, especially from February through April before convective activity in 2009 picks up. This reduction in streamflow and reduced flashiness has strong implications for riverine ecosystems and associated river ways. Changes in streamflow reflect changes in subsurface flow, soil moisture distribution, and water table levels across the watershed.

Changes in root zone soil moisture and associated changes in surface latent and sensible heat fluxes and surface layer humidity can in turn have a significant impact on vegetation cover. Although there is ample evidence in recent decades of changes in tree species in the Great Smoky Mountains National Park, North Carolina, Iverson and Prasad (2001) relying on statistical models of vegetation–climate patterns to examine the impact of five likely alternative climate regimes based on GCM simulations found no cause–effect relationship between climate and species richness. As mentioned earlier, this can be explained by the coarse spatial resolution of such climate models that cannot capture the altitudinal variations in climate as well as spatial variations in temperature, light availability, precipitation, and soil moisture states in mountainous regions. Using field data from nearly 20 years instead of model results, Clark et al. (2011) found that most sensitivity was to light availability. Because of the relationship between fog and light availability in the Great Smoky Mountains and that between fog, rainfall, and soil moisture, the surface energy budget and summer drought are strongly linked to climate and the water cycle, and one would expect significant changes in fecundity and increased vulnerability of tree species in the region of study because of changes in the precipitation regime (Zhu et al. 2011). Therefore, sensitivity to the governing hydrometeorological regime is especially important, as it articulates the need to explicitly include forests in mapping the physical hydroconnectivities of the landscape.

5.04.4.2 Land Conversion

Over the past 30 years, major land use transitions in mountainous regions consisted first of conversion of low-elevation croplands for urbanization, uphill expansion of agriculture, and urbanization through direct conversion of previously pristine forested areas to urban areas and to new housing developments. First, new development spreads in the valley

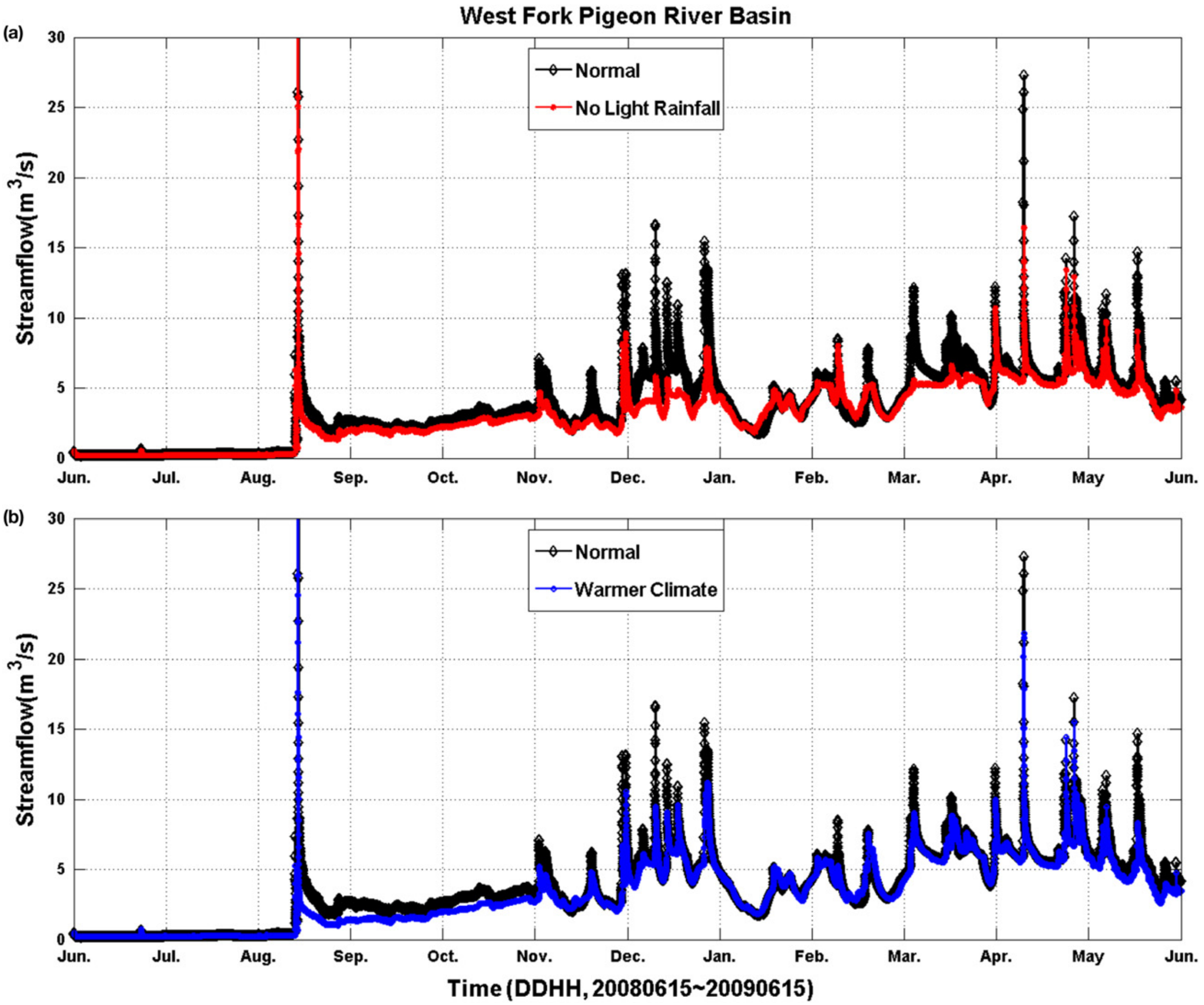

Figure 15 Rainfall-runoff sensitivity to potential changes in regional hydroclimate in a headwater catchment (~75 km^2 areal extent) in the Great Smoky Mountains, North Carolina, USA: (a) Jun 2008–May 2009, assuming all light rainfall ($<$3 mm h^{-1}) evaporates before reaching the ground; (b) Jun 2008–May 2009, assuming there is a contraction in the amplitude of the diurnal cycle of air temperature, which results from an increase of 2 °C at nighttime (6 p.m.–6 a.m. LST).

often where the floodplain is wider at the confluence of small tributaries, and then it penetrates upward the surrounding slopes. Land conversion in the next decades is expanding to the ridge areas, and in many regions of the world (e.g., the mid-Himalayas) this is the case already. Depending on local conditions, this results in increasingly fragmented landscapes.

Loss of natural vegetation cover and fragmentation of natural landscapes diminishes the landscape capacity to provide important ecosystem services, and when placed in realistic hydrogeological contexts and given the specificity of soil types and soil structure at local places, changes in land cover and land use strongly affect key hydroconnectivities and have a major impact on the water budget of headwater catchments. Using a coupled surface–subsurface model with dynamic vegetation at 1 km^2 to reconstruct the drought of 1988 and the wet year of 1993 in the Central Appalachians, Yildiz and Barros (2007) found that the two most important parameters controlling rainfall–runoff response on an event basis as well as the water budget at seasonal and annual time scales were vegetation fraction and leaf area index (LAI). On the other hand, warming of the lower troposphere can have a strong impact on fog–cloud and fog–cloud–rainfall interactions. The direct effects of fog and low-cloud suppression include changes of light and rainfall regimes, whereas the indirect effects have to do with the surface water and energy budgets and vegetation dynamics including vegetation replacement/succession (Figure 16). In Costa Rica, land use change associated with land use conversion from rain forest to agriculture in the lowlands has been linked to local changes in cloudiness and the elevation of cloud base over adjacent mountains (Lawton et al. 2001; Nair et al. 2003). We hypothesize that similar effects might occur elsewhere, for example, on the eastern slopes of the Andes due to clear-cutting in the Amazon.

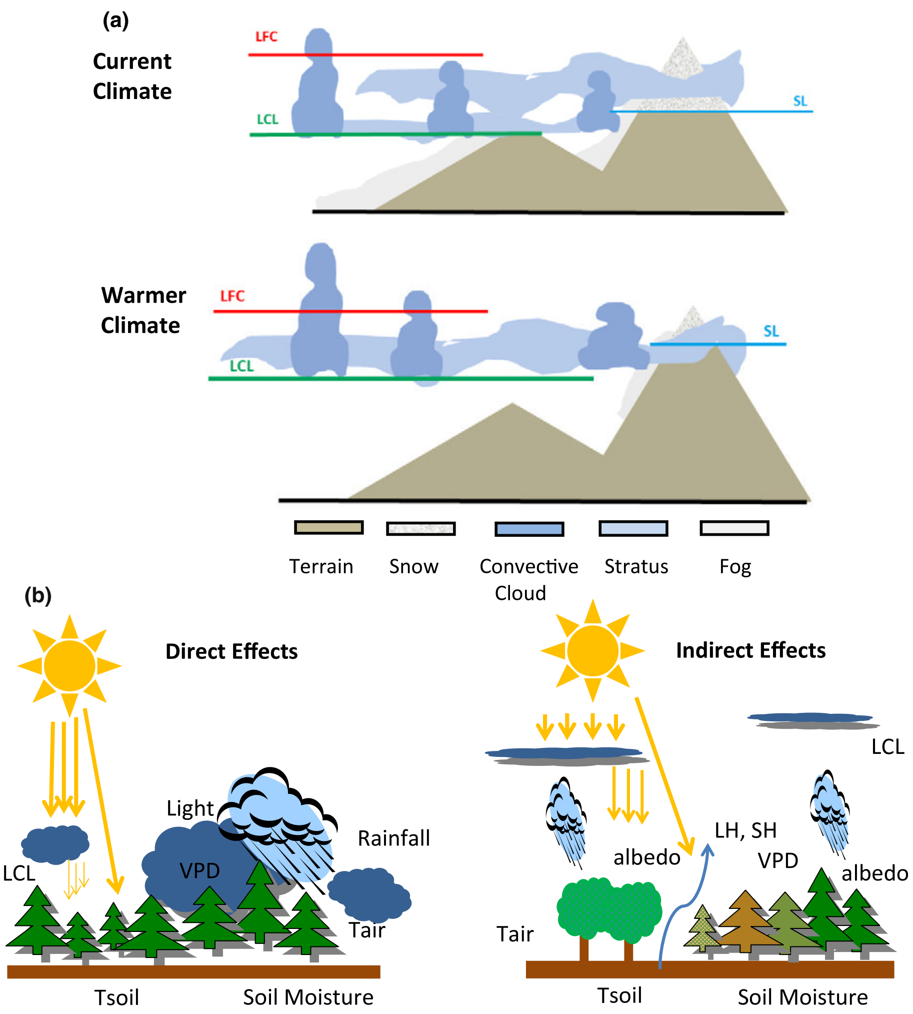

Figure 16 (a) Conceptual representation of changes in fog–cloud–rainfall interactions given an increase of regional lower troposphere temperatures that would impact the light rainfall regime. (LFC, level of free convection; LCL, lifting condensation level; SL, snow line); (b) Feedback of changes in fog–cloud–rainfall interactions toward increased aridity: left panel – direct effects (land surface forcing) include changes [+] in space–time patterns of light availability and incoming shortwave and long-wave radiation [+], vapor pressure deficit (specific humidity) in the lower troposphere [−], and rainfall [−] and air temperature [+]; right panel – indirect effects (land surface response and impacts on the planetary boundary layer) include changes in vegetation type (root structure, canopy, and color), albedo [−] and emissivity [+]; changes in latent [−] and sensible heat fluxes [+]; changes in soil temperature [+]; changes in soil moisture [−] and runoff [−]; changes in fog and low-level cloud morphology (thinner higher clouds, reduced fog) [−]; and LCL height [+] (VPD, vapor pressure deficit; Tair, air temperature; Tsoil, soil temperature; LH, surface latent heat flux; SH, surface sensible heat flux).

There is a vast literature in ecology addressing impacts of land conversion and the different modes of landscape fragmentation either due to natural changes or from forest clear-cutting practices (see review by Collinge 2009). Syphard et al. (2005) studied the effect of urban encroachment in the Santa Monica mountains in California. They found that development on steep slopes (>60%) lead to the largest habitat loss and more intense landscape fragmentation and connectivities. Various modes of spatial land use–land cover (LULC) change, including shrinkage, bisection, fragmentation proper, and perforation, will have different impacts on the dynamics of species competition and spatial variability. The challenge is to adaptively manage land conversion by preserving key hydro-connectivities including local microclimates, recharge areas, functional topsoils, and biodiversity, dampening indirect effects.

Besides human activities and climate, natural hazards, and in particular strong winds, fires, and landslides, can be important agents of rapid LULC transition. The vulnerability of landscapes to rapid disturbances is always high at short time scales, but moderate in the medium and long term if light and moisture regimes are conducive to recovery.

5.04.4.3 Mountain Snowpacks

Snow and ice are tightly connected to the climate at continental and global scales. Snow and melt processes are critical to characterize the mass balance of Arctic sea ice, which has been thinning at unprecedented rates (Kwok and Untersteiner 2011). The impacts from changes in the climatology of spatial patterns of temperature in cold regions are being felt at the global scale (Thompson et al. 2011; Koç et al. 2009). For instance, changes in snow cover, SWE, and winter–spring seasonality over the Eurasian region affect surface albedo and soil wetness, and strengthen or weaken the large-scale land–ocean temperature contrasts, including changes in Southeast Asian monsoon rainfall (Barnett et al. 1989; Qian et al. 2003, and many others) and changes in phytoplankton concentration in the Arabian sea (Goes et al. 2005). Feedback among clouds and snow-covered areas has a significant effect on the surface energy budget and the organization of local and regional-scale circulations. Global model predictions of snow cover-related feedbacks on the surface energy budget are difficult to assess because of the large uncertainties in predicting frozen precipitation amounts and spatial distribution. Even at weather-event scales and relatively high resolution, modeling uncertainties are very large, which prevent definitive impact studies as shown for the spatial distribution of albedo in **Figure 17** for two simulations using the Weather Research and Forecasting (WRF) 3.4 model at 18 km resolution, with everything being the same except the forcing used to drive the boundary conditions (**Figure 18**).

At high latitudes, it has been shown that the net daily radiation balance over snow surfaces is larger under cloudy sky conditions because of the increase in incoming long-wave radiation (Ambach 1974; Zhang et al. 2004). The magnitude of this enhancement depends on the cloud base, cloud base temperature, and cloud thickness, whereas an increase in air temperature accompanied by an increase in the moisture-holding capacity of the atmosphere can lead to significant changes in snowpack distribution due to the combination of two effects: (1) push the snow line to higher elevations (the elevation difference between locations of small glaciers in the Himalayas between current climate conditions and the last Glacial Maximum is on the order of 1000 m (Barros et al. 2006; Diaz et al. 2004)) and (2) more moisture at high elevations would increase snowfall and lower the cloud base, increase cloud depth and cloud cover, therefore warming the snowpack, increasing the likelihood of avalanches during snowpack ripening, and thus accelerating the onset of the melting season. This increases soil wetness early in the year, leading potentially to increased ET and reducing the contribution of snowmelt to river runoff or at least shifting it from the summer to spring. The impacts on agriculture and land management activities generally stem not only from changes in quantity but also, perhaps more critically in certain regions of the world, in timing of runoff and groundwater recharge (e.g., Koç et al. 2009; Lowry et al. 2010).

In Asia alone, eight of the world's largest river basins (from west to east, the Syr Darya, the Amu Darya, Tarim, Indus, Ganges, Brahmaputra, Mekong, Yangtze, and Yellow River) affecting roughly 1.5 billion people depend on glaciers and snow at high elevations to maintain river flows (see Figure 21 in Nellemann et al. 2009). In the western United States, more than 70% of the water resources are generated during the spring melting season and subsequently stored behind dams for a broad range of water uses during the dry season (Stewart et al. 2004). Fundamental challenges in snow measurement, including specifically the need for high-resolution estimation of snow wetness and snow density, point out the importance of the so-called transition zone in mountainous regions where the fractional contributions of snow and rain to the total annual precipitation are highly variable in space and time, and wetter and warmer snowpacks during the cold season are thus more unstable. Trends in historical observations and simulated changes from GCM simulations suggest that large shifts in the spatial and temporal availability of freshwater resources from snow could occur (e.g., Knowles et al. 2007; Brown and Mote 2008; Pepin and Lundquist 2008; Stewart et al. 2004; Stewart 2009). Yet, the density of climate observations is the lowest for

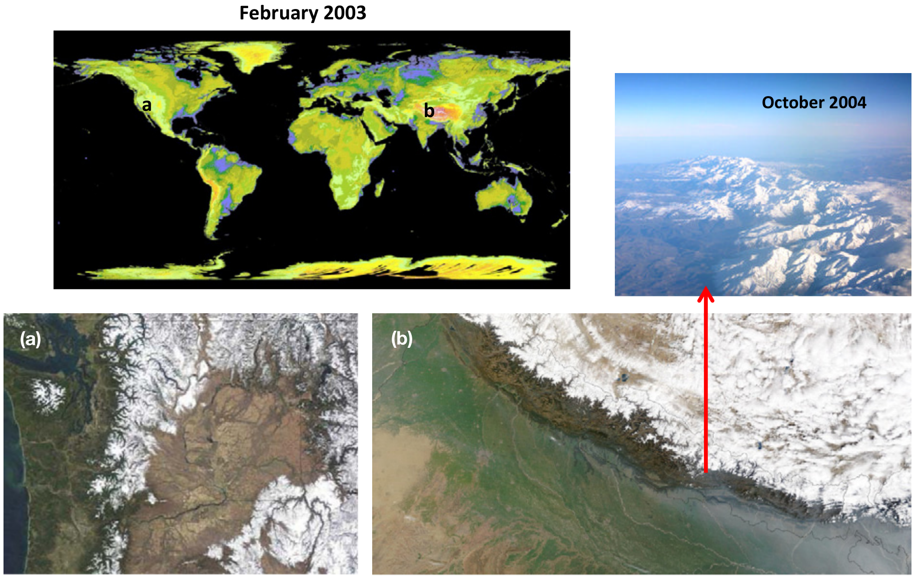

Figure 17 Snow cover distribution in February 2003 observed using the MODIS sensor on the Terra satellite: (a) Columbia River basin; (b) Himalayan range. Source: MODIS–NASA; Photo: http://www.himalaya-foto.ru.

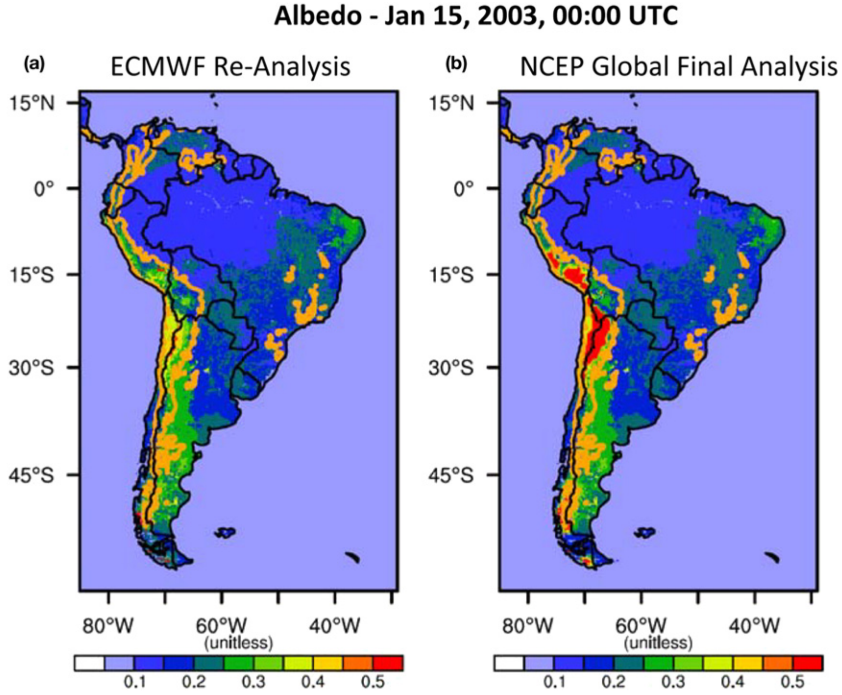

Figure 18 Snow albedo over the Andes for a WRF V.3.4 (weather research and Forecasting model) simulation of during the wet season in model simulations using two different large-scale forcing data sets: (a) ECMWF Reanalysis (ERA) and (b) NCEP Global Final Analysis (FNL). The differences in albedo reflect the different distribution of frozen precipitation in the two simulations, and provide a measure of the uncertainty in surface energy balance calculations in the Altiplano, which in turn affects large-scale circulation.

frozen precipitation and snow and ice accumulation including the rain–snow transition elevation (Viviroli et al. 2011, Figure 19).

5.04.4.4 Water Resources Governance

Rogers and Hall (2003) define water governance as the range of political, social, economic, and administrative systems established for the development and management of water resources and water services at all scales (Figure 20). It needs to be considered at basin and subbasin scales, and within sectors (e.g., agriculture, urban water supply) and intersectorally, and should encompass the management of the land use and hydroconnectivities within a basin that affect the characteristics of the resource downstream. It includes establishment of rules, responsibilities, operating mechanisms, policies, and user and official accountability systems. Effective governance is that which provides water for livelihoods and economic growth, yet maintains a sustainable environment. Each river basin has its own physical, social, environmental, and economic characteristics; is at a particular level of development; and has its own unique form of formal and informal governance systems in place, which are characterized by the particular social, cultural, and political setting of that basin. At the same time, many of the world's basins are becoming increasingly over-allocated, or stressed in other ways, such as through increased population density, urban sprawl, agricultural expansion, and pollution (Vörösmarty et al. 2010). In the case of mountainous regions, the challenges due to progressive encroachment of anthropogenic activities upon headwater basins that control freshwater resources and thus water supply downstream may differ in the details on account of regional specificities, but not in substance, and the stressors are fundamentally the same in North and South America as in Asia.

It is increasingly acknowledged that even in the least developed parts of the world there needs to be a basic platform of water-systems infrastructure for effective water governance to support the needs of the society and economy (Grey and Sadoff 2007). In the United States, the water resources governance tends to be highly codified, in terms of regulations, rules, and laws, with strong yet relatively diffuse institutions. Missing in terms of both infrastructure and institutions in the US and elsewhere is the capacity to adapt to change, especially when change is fast and driven by multiple stressors: climate variability and longer term change, population growth, economic development, and natural resource management practices and policies. Active involvement of stakeholders in the decision-making process, however, often only takes place in terms of protecting and ascertaining water use rights locally especially when crisis strikes (e.g., drought). A contrasting example is the Ganges River in South Asia, where patterns of water flow and utilization in the basin are changing, and in some subbasins very rapidly. Water governance in the smaller catchments is relatively nonexistent apart from basic community level efforts and, at the river basin scale, is defined based on macro considerations by a concentrated authority at high government level.

Sustainable water systems function optimally in the context of evolving human and natural landscapes to capitalize water availability at short time scales and to balance water demand and ecosystem services over long time scales. It is well accepted

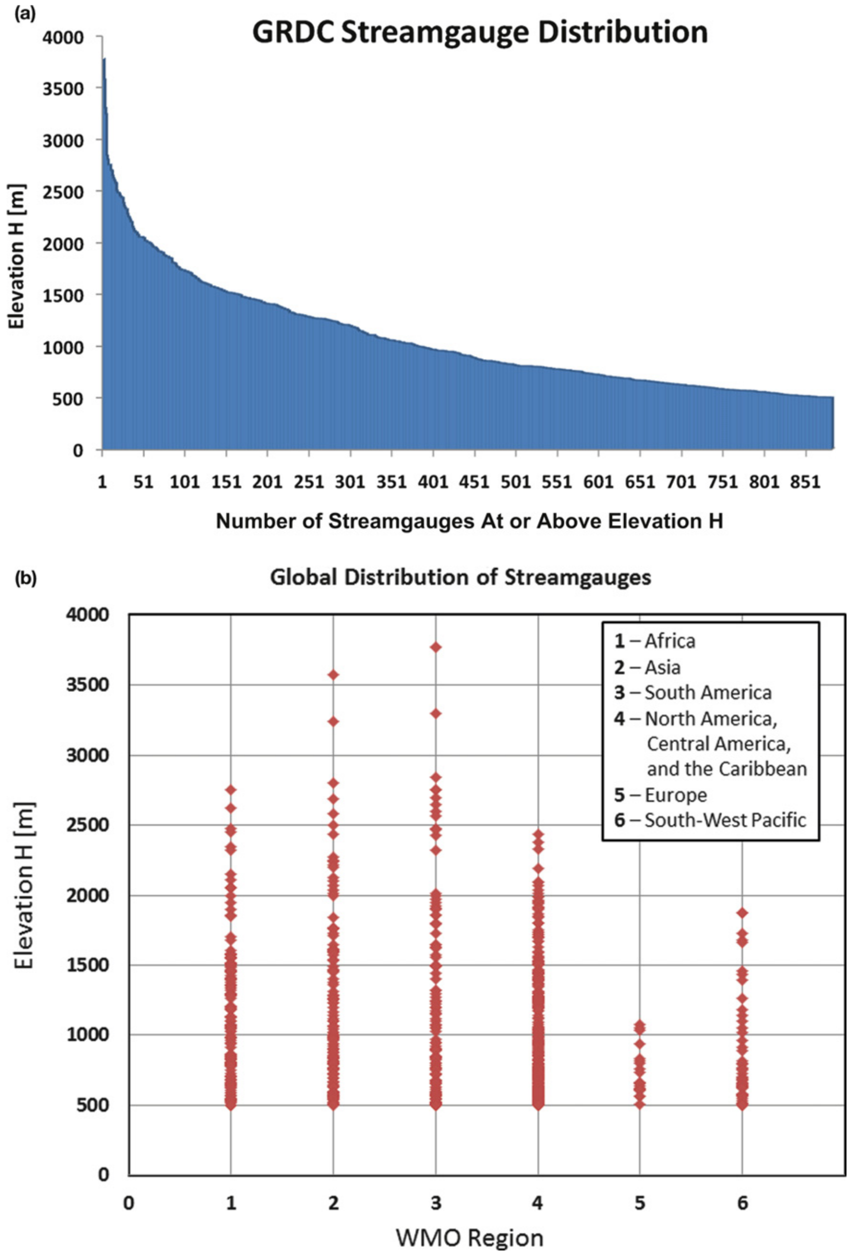

Figure 19 Global distribution of Streamgauges: (a) as a function of elevation; (b) for each elevation as a function of World Meteorological Organization (WMO) regions. Source: http://www.bafg.de/GRDC/EN.

that this can be accomplished only by combining the best science and predictive models with vigorous, participatory water governance spanning a wide range of spatial and temporal scales and policy horizons (Falkenmark and Rockström 2006). Although access to the necessary financial resources to adapt infrastructure and the institutions may be less of a challenge in the United States, the ability to adapt at a rate and in a manner that reflects the best end-to-end understanding of the underlying water systems is lacking. Effective water management that integrates both society and ecosystems needs is key to climate adaptation. Besides the importance of relying on science-based predictive models, there remain important disconnects between the technical and science-based knowledge of water resources management and the broader governance aspects, such as the participation of the community, stakeholder involvement in the basin management process, relationships between the water resources systems, and changes in key sectors, such as industry and agriculture. Where the capacities and resources are available, nimble response to change by reevaluating zoning plans, switching cropping patterns, revisiting reservoir operation plans, development of new storages and other infrastructure, including early warning systems, and enhancing institutional arrangements can result in sustainable adaptation.

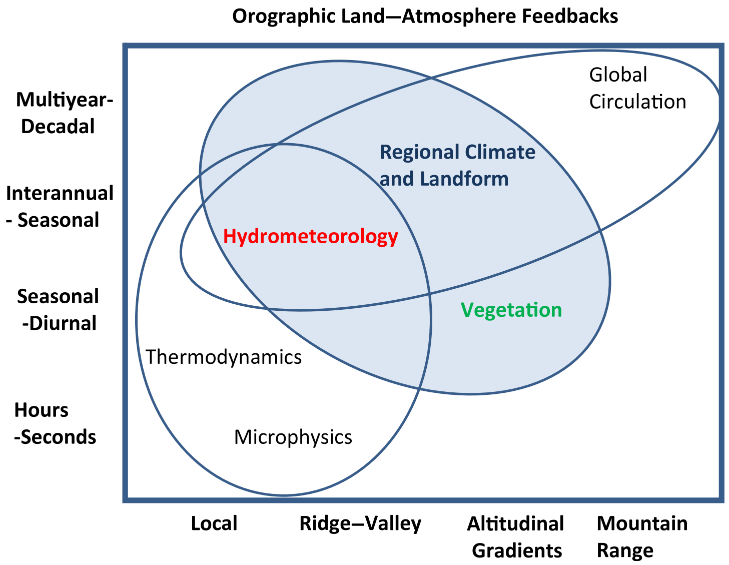

Figure 20 Schematic of processes and scales of orographic land–atmosphere interactions and direct and indirect fog–cloud–rainfall feedbacks.

5.04.5 Synthesis

Mountains play a critical role in modulating the water cycle at regional scales beyond the spatial presence of the mountain proper reaching out to the adjacent plains of the world's largest river basins. Orographic effects negotiate the regional harvest of large-scale moisture transport at seasonal scales, and complex space–time patterns of landform and vegetation determine the diurnal cycle and 3D organization of mountain microclimates (Figure 20). Local fog–cloud–rainfall interactions conspire to sustain the light and moisture availability regimes that nurture mountain vegetation in a crescendo orchestrated along altitudinal gradients depending on increasingly more delicate feedbacks with elevation. In this chapter, the case was made that fog and light rainfall are the water lifeline of mountain environments, whereas extreme events are the agents of short-term disturbances. The challenge of adaptation to change and sustainability of mountain freshwater resources hinges on our ability to understand and manage the dynamic balance between disturbance and resiliency, and this includes environmental policy and water and land governance matters. In mountains, perhaps more critically than anywhere else, and paraphrasing Falkenmark, a land use/land cover decision is a water decision. The reverse is also true. Mountains remain among the most poorly observed environments in the planet. Improving fog, clouds, and rainfall observing systems, yet so sparse in mountainous regions, is essential to understand and to make sound sustainable water decisions.

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5.05 Tropical Montane Cloud Forests

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5.05.1 Tropical Montane Cloud Forests and Their Relationship to Water Input

Tropical montane cloud forests (TMCFs) are unique tropical ecosystems that occur as narrow altitudinal bands between 800 and 3500 m on mountains in the continents of Africa, America, and Asia and in equatorial Oceania (Bubb et al. 2004; Kapelle 2004; Bruijnzeel et al. 2011) (**Figure 1**, also see **Figure 1** of Bruijnzeel et al. 2011). The defining characteristic of TMCFs is persistent cloud cover/fog at the vegetation or ground level that ensures that the tree crowns are regularly in contact with cloud water. The cloud water in turn contains drops of an entire spectrum of sizes from suspended droplets to falling rain-sized droplets. Cloud water directly condenses on the vegetation surface in TMFCs as precipitation. This phenomenon is variously referred to in the literature as 'horizontal precipitation,' 'direct interception,' or 'cloud water stripping.' The cloud water that is deposited regularly on the vegetation surface is primarily from orographically lifted air masses that cool to form the clouds (**Figure 2(a)**), although orographically lifted advection fog, sea fog, steam fog, or radiation fog could also provide a source for horizontal precipitation (Scholl et al. 2010).

The singular distinguishing feature of regular immersion in clouds and cloud water input to TMCFs has important implications to vegetation characteristics, vegetation productivity, nutrient uptake, soil and litter composition, and a positive water balance (**Table 1**). This process is especially important for dependable streamflows in areas downstream that have little dry-season precipitation but where cloud forests are present upstream (Bubb et al. 2004). This unique feature of TMCFs also results in higher species richness and higher biological endemism within the TMCF (Foster 2001; Bruijnzeel et al. 2011). Three types of TMCFs are now recognized: lower montane cloud forest, upper montane cloud forest, and subalpine cloud forest (Bruijnzeel et al. 2011). The transition from lower to upper montane cloud forest coincides with the level where cloud condensation becomes more persistent, whereas that from upper to subalpine TMCF occurs at the altitude where the average maximum temperature falls below 10 °C (Bruijnzeel et al. 2011). The current estimates of global spatial extent of TMCFs vary widely from 21 5000 km^2 to 2.21 million km^2 (Bruijnzeel et al. 2011), partly due to the difficulty of identifying which tropical forests are regularly cloud immersed forests, although remote sensing techniques provide promising new approaches (Nair et al. 2008; Welch et al. 2008; Lawton et al. 2010; Ray et al. 2011). Bubb et al. (2004) estimated that 2.5% of all tropical forests are cloud forests, with the lowest percentage in the Americas (1.2%) followed by Africa (1.4%) and Asia having the highest percentage (6.6%).

Owing to adaptation to regular cloud water interception, TMCF species are vulnerable to droughtlike conditions. Epiphytes, which grow on other plants in the TMCF and derive their moisture from the air, are a defining characteristic of cloud forests, where a quarter of all plants may be composed of various species of epiphytes (Foster 2001). Epiphytes are especially vulnerable to changes in regular cloud water immersion since they can only access intercepted water through organs dedicated to uptake of water deposited on them. Short intense pulses of rain events are thus relatively of little use to epiphytes. However, in many TMCFs, a significant proportion of the water input could be from continuous drizzle that keeps the organs for water uptake, such as roots, wet. Persistent fogginess also has led to specialist anuran and avian species that are adapted to specific altitudes corresponding to cloud frequency of immersion.

5.05.2 Stability of Tropical Montane Cloud Forests

The pressure to feed a growing and wealthier global population and grow biofuel crops has resulted in a net increase of the world's croplands and pastures by 154 million hectares between 1985 and 2005, which included significant expansions in the tropics and losses in the higher latitudes (Foley et al. 2011). It is estimated that 80% of new tropical croplands are from the conversion of forests (Gibbs et al. 2010). TMCFs are clearly threatened from these direct conversions into agricultural and pastoral lands and other developmental activities such as road constructions, building of dams and reservoirs, and mining activity (Ray et al. 2011). However, even when TMCFs are protected, they are affected indirectly by global, regional, and local processes that change the very critical 'regular immersion in clouds' process via changing the upper and lower bounds of clouds, cloud thickness, cloud cover and its frequency, cloud water content, and temperature changes.

5.05.2.1 Impacts of Global Changes

Changes in global scale processes impact TMCFs because the global scale atmospheric circulation of the Hadley cells determines the altitude of the trade wind inversion layer that in turn marks the upper bound of cloud top heights in the tropics.

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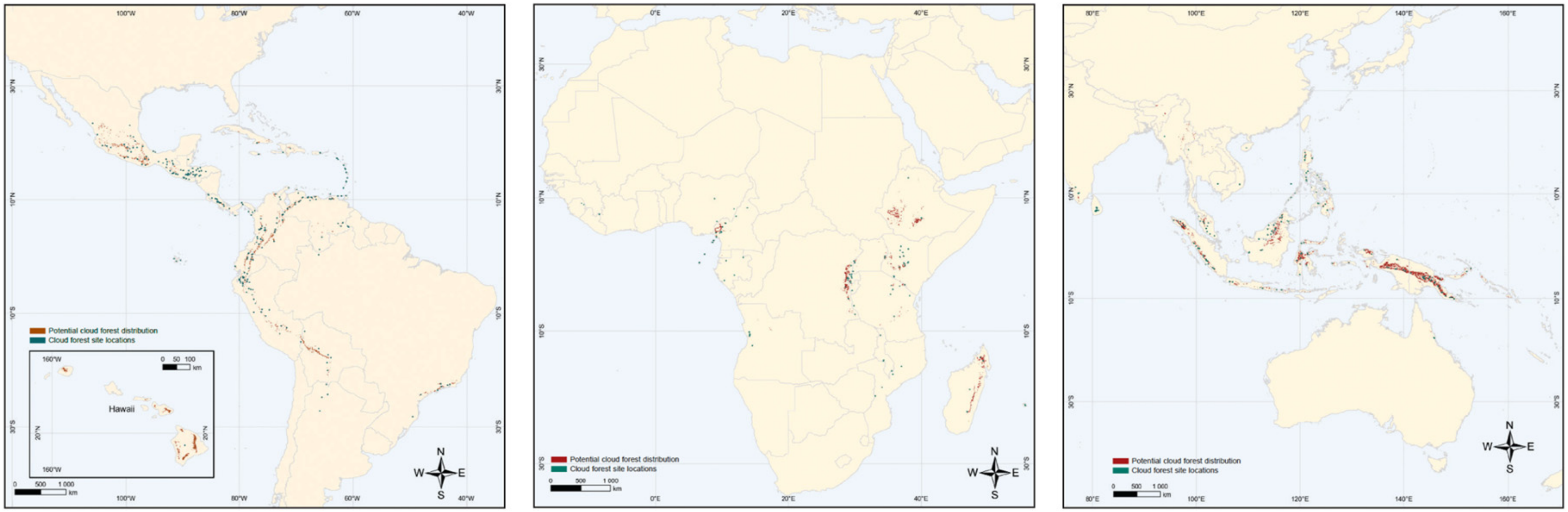
100°W
80°W
60°W
40°W
30°N
10°N
10°S
30°S
Potential cloud forest distribution
Cloud forest site locations
160°W
Hawaii
20°N
0 50 100 km
0 500 1 000 km
N
W
E
S
0°E
20°E
40°E
80°E
100°E
120°E
140°E
160°E

Figure 1 Global potential (red) and known (green) TMCF distribution. Reproduced from Bubb, P., I. May, L. Miles, and J. Sayer, 2004: *Cloud Forest Agenda*, UNEP-WCMC, Cambridge, UK. [Available online at http://www.unep-wcmc.org/biodiversity-series-20_105.html].

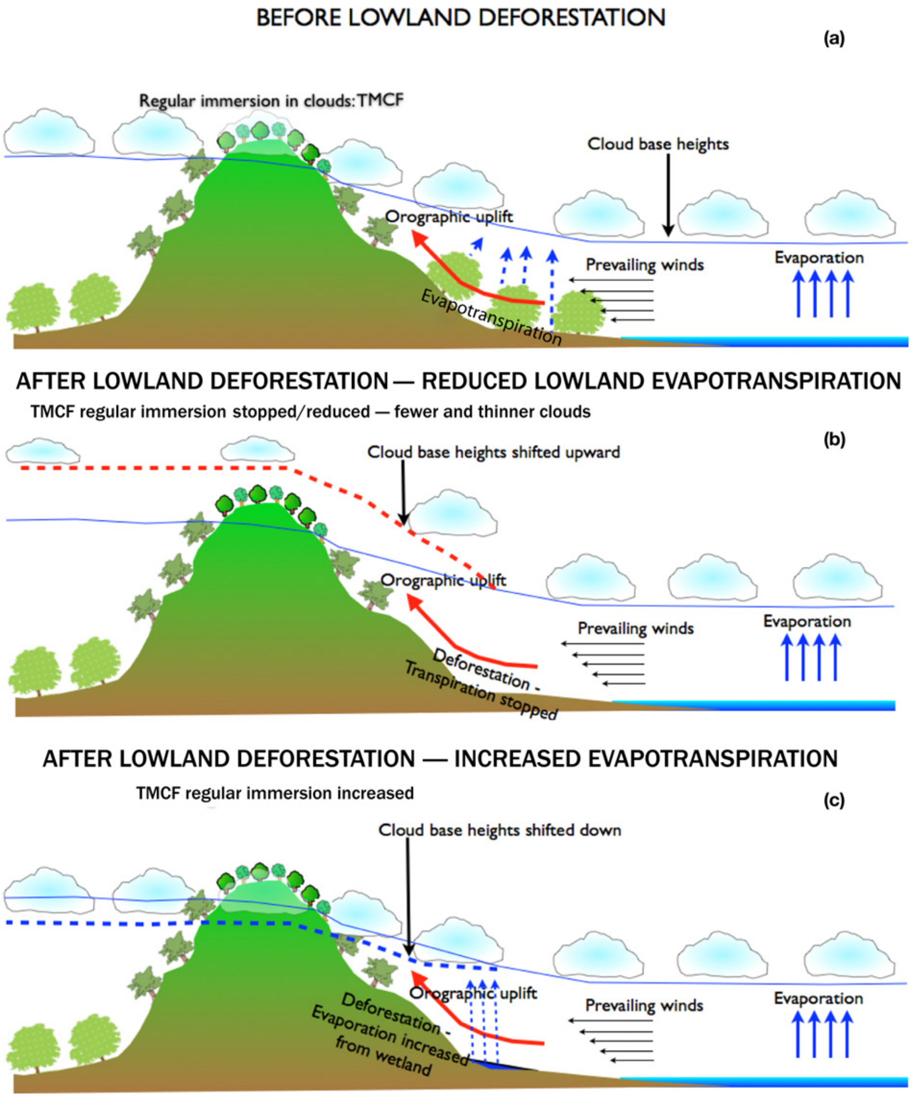
BEFORE LOWLAND DEFORESTATION
(a)
Regular immersion in clouds: TMCF
Cloud base heights
Orographic uplift
Prevailing winds
Evaporation
Evapotranspiration
AFTER LOWLAND DEFORESTATION — REDUCED LOWLAND EVAPOTRANSPIRATION
TMCF regular immersion stopped/reduced — fewer and thinner clouds
(b)
Cloud base heights shifted upward
Orographic uplift
Prevailing winds
Evaporation
Deforestation - Transpiration stopped
AFTER LOWLAND DEFORESTATION — INCREASED EVAPOTRANSPIRATION
TMCF regular immersion increased
(c)
Cloud base heights shifted down
Orographic uplift
Prevailing winds
Evaporation
Deforestation - Evaporation increased from wetland

Figure 2 Effects of lowland land-use change on TMCF. (a) Current conditions. (b) Lowland deforestation reduces evapotranspiration and pushes cloud base heights upward. (c) Lowland deforestation increases evaporation from wetlands and lowers cloud base heights.

The trade wind inversion layer in turn is due to the descending branch of the Hadley cells and compression and warming of the air (Bruijnzeel et al. 2011). The altitude at which the orographically forced trade winds begin condensing clouds on the other hand determines the cloud base heights and thus the lower bound of the TMCF. The movement of the Intertropical Convergence Zone (ITCZ) also determines the timing and length of the wet season over the TMCF.

During the last glacial maximum, the drastically altered global conditions of temperature and precipitation influenced the spatial and altitudinal distribution of TMCFs. Lake pollen records from Andean TMCFs during the ice ages and modeling results show downslope expansion of TMCF species during the conditions of reduced temperature and wetter conditions that existed and consequently lowered cloud bases (Still et al. 1999; Urrego et al. 2005). Lowering of cloud bases allowed the TMCF

Table 1 Principle hydrometeorological and vegetation characteristics of TMCFs

Climate	*Vegetation*	*Productivity*	*Water balance*
High cloud frequency	High endemism	Low photosynthesis rates	Additional water input from horizontal precipitation
High relative humidity	High proportion of epiphytes	Low net primary productivity	Low transpiration and physical evaporation
Low irradiance	Stunted trees with small thick and hard leaves		Streamflow/incident rainfall very high

Adapted from Foster, P., 2001: The potential negative impacts of global climate change on tropical montane cloud forests. *Earth-Sci. Rev.*, **55,** 73–106.

species to colonize the lower elevations. Other studies, however, from Andean TMCFs suggest that during the ice ages aridity increased and fragmented the TMCF (e.g., Mourguiart and Ledru 2003). Clearly, global climate has a profound impact on TMCF spatial and altitudinal distributions.

Looking forward, atmospheric carbon dioxide has continued to increase, reaching a globally averaged concentration of 387.2 ppm at the end of 2009 (Friedlingstein et al. 2010). The technological advance required to stabilize greenhouse gas emissions, however, could be unachievable (Pielke et al. 2008), and emissions of carbon dioxide and other greenhouse gases are expected to continue; global climatic changes are occurring via altering the radiative balance of the earth's ocean–atmosphere system. Future globally averaged warmer conditions at the surface could result from these elevated greenhouse gases, which would increase evaporation from the water bodies that supply moisture leading to more cloudiness. However, at the same time, the condensation level for clouds could increase because of the warmer air thereby reducing cloud cover and the frequency with which cloud immersion occurs at the vegetation level (Still et al. 1999). It is not clear which process would dominate: more humidity and lowered cloud bases or more humidity but higher cloud bases due to warmer air masses at each TMCF site. Nor is there certainty of global climate changes being felt at each TMCF site. However, if the current regime of cloudiness and temperature changes for any reason, it could lead to the shifting of the current species composition, favoring those that are more adapted to the new conditions and extinction of others. Lack of cloudiness, for example, has been implicated in the outbreak of fungal diseases and species extinction of endemic TMCF fauna (e.g., Pounds et al. 2006).

Unfortunately, future cloud immersion is nearly impossible to predict at the individual TMCF locations, and studies that predict future conditions can only indirectly estimate the cloud immersion process via changes in other variables such as relative humidity (Still et al. 1999). This is because of multiple reasons: global climate models have coarse resolutions with each climate model grid cell representing areas of more than 1° of latitude–longitude, whereas TMCFs generally occur only as narrow altitudinal belts of less than a degree of latitude–longitude. Moreover, not only do TMCF belts occur as subgrid-scale regions within global climate model grid cells but the global climate models also parameterize subgrid-scale phenomena such as smaller scale clouds that are primarily the ones that bathe TMCF (Lawton et al. 2001). This means that even if global climate models could accurately predict the future climate, future cloud conditions at the vegetation level of TMCFs cannot be directly determined from global climate model simulations. While regional-scale dynamic downscaling from global model forecasts could provide future cloud frequency at the TMCF resolution, it is now quite clear that regional-scale downscaling is unable, at present, to add any value beyond what is already available via historical analyses, recent paleohistory, and worst case sequence of observed weather (Pielke and Wilby 2012). Under such conditions, a bottom–up assessment of historical regional processes that impact TMCF stability is more useful in understanding the indirect hydrometeorological threats to TMCFs. In order to make this assessment, what do past observations and modeling at TMCF sites tell us about their hydrometeorological vulnerability?

5.05.2.2 Impacts of Regional Changes

Modeling and observational studies show that regional land-use change could either raise or lower the altitudes of cloud formation, i.e., cloud base heights, but the magnitude of the impact is highly site specific. Generally, if the air column gets increasingly warmer and drier while traversing the landscape from the moisture sources before being forced to rise orographically, the altitude at which clouds form (cloud base height) also gets raised (Figure 2(b)). Not only the cloud base heights but also the thickness of clouds, cloud water content, and cloud immersion frequency could get reduced, thereby changing the hydrometeorological environment of the TMCF and subsequently its ecology, irreversibly. The amount by which the clouds are impacted differs based on the amount of upwind deforestation, new land use, and sea surface temperature changes. Inland cloud forests like those of southern Mexico and Costa Rica may be profoundly influenced by regional deforestation (Lawton et al. 2001). Multiple numerical modeling simulations from the Monteverde TMCF of Costa Rica (Nair et al. 2003; Ray et al. 2006) show how deforestation reduces cloud cover at the TMCF vegetation level.

Originally, tropical moist and wet forests covered most of the Costa Rican lowlands. However, by 1992, deforestation had reduced the forest cover in the lowlands to only 18% of the original forest cover (Veldkamp et al. 1992; Ray et al. 2006). Deforestation converted the forest trees that have a deeper root system into the shallower rooted agriculture (pasture grasses and seasonal agricultural crops have shallower roots, although tree plantation agriculture could have deeper roots). Field observations suggest that trees have access to water stored in deeper soil layers unlike cropland species (Ray et al. 2006). Studies from eastern Amazonia have also shown that up to 75% of all the water extracted during the dry season originates from soil layers below 2 m, which only trees can access (Nepstad et al. 1994). Thus, as the dry season progresses in Costa Rica's lowlands, evapotranspiration reduces, but because of conversion to cropland it now reduces drastically. This is affecting the cloud cover.

Nair et al. (2003) noted that patterns of cloud formation over the forested lowland regions in Costa Rica exhibited linear organization, but over the deforested areas the convection was unorganized. According to them, organized convection over forested lowland areas was indicative of reduced sensible heat fluxes over forests compared to deforested areas. Souza et al. (2000) via measurements of dry-season surface energy fluxes over paired forested–deforested sites in Amazonia showed a pattern similar to that found by Nair et al. (2003) for Costa Rica. The mechanism is explained in the extensively validated modeling study of Ray et al. (2006). The trade winds that blow over the now extensively deforested Atlantic lowlands of Costa Rica during the dry season encounter drier and warmer air due to the reduced evapotranspiration. Via turbulent mixing with this drier and warmer air the trade winds get drier and warmer (Figure 2(b)). It takes the trade winds around 5–10 h to traverse the extensively deforested Atlantic lowland areas of Costa Rica when this mixing process occurs (Lawton et al. 2001). If the lowlands were forested instead, it is very likely that transpiration would be higher because of trees accessing deeper soil moisture and thus the trade winds would have mixed with cooler and moister air. This in turn would dry and warm the trade winds comparatively less than what happens currently (**Figure 2(b)**). When these modified air masses from the lowlands now rise up orographically, the altitude at which water vapor begins to condense into cloud droplets is higher; in other words, the cloud base heights have been raised because of the extensive deforestation of the lowlands. Ray et al. (2006) estimate that this impact is greatest in the afternoon hours and has already reduced the areal coverage of cloud immersion by 5–13% because of the ~75-m rise in cloud base heights. They estimate that further lowland deforestation could reduce the spatial extent of cloud immersion by another 15% via another ~125-m rise in cloud base heights.

There are similar bottom–up evidences from other sites as well. Barradas et al. (2010) show that the widespread conversion of cloud-affected montane forests to agriculture and pastures in central Veracruz, eastern Mexico, is affecting the climate. There is an observable altitudinal shift in dry-season precipitation (notably in February), and overall fog frequency has also reduced. Ray et al. (2011) have also shown that if the lowland areas of the Western Ghats in southwest India are further deforested then the cloud base heights would increase in the dry season. This is similar to the mechanism reported from Costa Rica. However, unlike in Costa Rica where precipitation is also expected to reduce with further deforestation (Ray et al. 2010), over the Western Ghats precipitation could contrarily increase in the dry season, although cloud immersion reduces. On the other hand, coastal forests like those of some Caribbean islands (e.g., the Luquillo forest of Puerto Rico) may have too little upwind lowland to experience any lowland deforestation impacts (Lawton et al. 2001). While this may be true for many other coastal TMCFs, Van der Molen et al. (2006, 2010) have suggested a different mechanism and found decreases in cloud base heights and precipitation with deforestation (**Figure 2(c)**). On the other hand, using historical model simulations, Comarazamy and González (2011) have implicated climatic change as impacting the cloud base heights and precipitation in Puerto Rico's TMCFs.

While the studies of Van der Molen et al. (2006, 2010) and Comarazamy and González (2011) may disagree on the exact mechanism that lowered cloud base heights and reduced precipitation, they were both also partly conducted because water supply in Puerto Rico decreased in the 1990s and led to water rationing, affecting millions (Van der Molen et al. 2010). According to Van der Molen et al. (2006, 2010), deforestation reduced the sensible heat flux because the pastures of Puerto Rico that replaced the forests were well-watered long grasses. Thus, under clear and calm conditions, when the sea breeze dominates the trade wind flow, reduction in sensible heat flux from deforestation reduced the strength of the sea breeze, resulting in lower cloud base heights, but the reduced uplift also lowered the precipitation. Comarazamy and González (2011), however, found a global warming signal driving the reductions in precipitation in Puerto Rico. According to them, between 1955 and 2000 the lower atmospheric temperature has increased between 1.0 and 1.8 °C over the Caribbean region but much higher toward the North Atlantic. This has created a pressure difference between the two regions that has intensified and also changed the flow direction of the trade winds in such a way that the axis of the orographic uplift has itself shifted. The new flow direction has reduced orographic uplift over the TMCF sites and reduced precipitation, although higher humidity has increased cloud thickness, thus appearing as lowering of the cloud bases.

Clearly, there is a lot of variation in the exact mechanism even at a site, and at different times different mechanisms may dominate, but similar bottom–up investigations are urgently required elsewhere to determine the most dominant process and the conditions under which they would dominate. One of the key determining factors for the cloud base height and its prediction at each TMCF site is measuring the Bowen ratio – the ratio of sensible heat flux to latent heat flux. As evapotranspiration reduces, radiative balance is achieved via increased sensible heat flux, and the Bowen ratio increases. A higher sensible heat flux triggers stronger updrafts and higher cloud base heights. Thus, cloud base heights are lowered with lower Bowen ratios (Foster 2001). Historical global climate signals such as those of Comarazamy and González (2011) provide additional layers of information. For example, under calmer conditions, local processes could dominate, and clearly, the nature of the lowland land use would then impact the TMCF. In other places such as Costa Rica, even when the trade winds dominate, the nature of lowland land use would impact the TMCF, as the trade winds mix for long periods with the air column over the lowlands during which they can be significantly modified prior to orographic uplift. Unfortunately, while it is quite clear that similar bottom–up observations and modeling exercises are required, the continent with the largest proportion of TMCF, i.e., Asia, is the least studied and the Americas with the least proportion of tropical forests as TMCFs are the most studied.

In general, at each TMCF site, the hydrometeorological conditions are being simultaneously impacted from global, regional, and local factors, but one or more of these generally dominate. Moreover, the occurrence of montane cloud forests and the thickness of the cloud forest belt itself are governed by the altitude of persistent cloud condensation, which needs to be urgently determined to establish a baseline against which changes could be measured. What is, however, clear is that with increasing distance from the ocean, air tends to be drier and therefore requires lower temperatures and higher elevations to reach its condensation point. Consequently, the associated cloud base and TMCF vegetation will occur at higher elevations farther from the oceans. Likewise, at given moisture content, the condensation point is reached more rapidly by cooler air than by warmer air. Thus, at greater distances from the equator, the average temperature, and therefore the altitude at which condensation and TMCFs occur, will be lower. If land-use change reduces evapotranspiration into the air masses as they travel from the oceans to the mountains then the cloud bases will rise and cloud forests at lower elevations will become unstable and vice versa. If global climate changes the direction of flow, then cloud formation will change and TMCFs will become unstable.

5.05.3 Bottom–Up Solutions

Currently, the most serious challenge being faced by TMCFs is from economic activities that are directly destroying

TMCFs – construction of roads and other infrastructure, timber and mineral extraction, telecommunication facilities, tourist development (including golf courses), hydropower production, illegal plant collection, excessive and inappropriate tourism, and steady encroachment of agriculture (Kumaran et al. 2010; Meyer 2010; Owiunji and Plumptre 2010; Ray et al. 2011). The loss of cloud forests can even induce fires and destroy other areas of the cloud forest. Other destructive activities include grazing or trampling by feral ungulates and invasion by alien plant species (Meyer 2010). Some areas that lost TMCFs are now being allowed to recover because of changed political, economic, and social drivers (Aide et al. 2010). TMCF recoveries are, however, hampered from competition with invasive grasses and ferns and poor seed dispersal (Aide et al. 2010). One of the most cost-effective ways to accelerate the recovery of TMCFs is to promote the establishment of shrubs, which helps to shade out invasive grasses and ferns and create more appropriate conditions for seedling growth. This strategy reduces the competition faced by the original TMCF plant species, but clearly, not all TMCF species will recover successfully. Thus, planting will also be required to recover a species composition similar to the intact forest because most forest species are rarely dispersed far from forest stands (Aide et al. 2010).

Where modeling studies have already shown that conversion of lowlands to shallow-rooted agriculture impacts TMCF cloud immersion, deforestation should be immediately stopped to prevent any further reduction in the frequency with which cloud immersion occurs. In areas where no assessment has yet been done, modelers should make extra efforts because the rates of lowland deforestation is very high in the tropics and is expected to continue in the near future. Historical simulations such as those of Comarazamy and González (2011) should be done to determine climate impacts. A global effort with focused local action in which researchers, governmental agencies, local authorities, NGOs, private enterprises, and civil society all work together is urgently required (Bruijnzeel et al. 2010).

Finally, relevance to the conservation of biodiversity is the most common justification for conducting research not just about TMCFs but also in all biology-related tropical research. A study by Pitman et al. (2007) shows that there is a distinct disconnect between 'foreign researchers' and the perceived beneficiaries of the research. Foreign authors tend to focus on basic science that the on-the-ground beneficiary cannot understand; publish their results in very expensive academic journals in which they cite each other but that the beneficiary invariably cannot access; publish in English, which most of the beneficiaries cannot read, and have few explicit conservation recommendations. On the other hand, 'gray literature,' written mostly by on-the-ground practitioners of conservation in the tropics is related to management, not digitally available, non-peer reviewed, and in a non-English language that 'foreign researchers' cannot access. For the bottom–up process to really succeed for TMCF conservation "scientists in the tropics, regardless of their nationality" need "to examine and reexamine the practical connections between the work they do and the work done by those who manage tropical lands. For scientists whose funding derives from grant proposals that invoke the critical environmental situation in the tropics, this is practically an ethical obligation" (Pitman et al. 2007).

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5.06 Climate Vulnerabilities and Adaptation of Urban Water Infrastructure Systems

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5.06.1 Introduction

Urban water infrastructure systems provide for water supply, stormwater management, and wastewater collection and disposal (Figure 1). In the United States and most developed nations, these systems comprise extensive networks of physical infrastructure interconnected with natural waterways and are managed by a collection of large centralized institutional entities defined according to political and jurisdictional boundaries instead of watershed boundaries. Water supply systems begin at a source of water (e.g., lake, river, stream, spring, ocean, aquifer, reservoir) followed by extraction or diversion into an infrastructure network that treats, stores, and distributes the water to users. Stormwater management systems direct surface runoff into a connected network of gutters, channels, pipes, ponds, and other components. Typically, stormwater is infiltrated, retained in control structures, or detained and directed untreated into streams, rivers, lakes, and coastal waters. Wastewater, in general, is managed using two approaches. In most areas of rural and low-density development, wastewater is disposed of using septic systems; in denser metropolitan areas, wastewater is collected in sewer networks, conveyed to treatment facilities, and treated prior to discharge. Each of these urban water infrastructure systems is vulnerable (i.e., may be adversely affected) to climate, land use change, population growth, socioeconomic development, increasing per capita water demand, aging and deteriorating infrastructure components, regulations, and behaviors (Figure 1).

The impact of urbanization and population growth are the predominant, and in most cases, only factors considered in planning and design of urban water infrastructure systems. Changes in landscapes to urban or new urban uses may modify land surface, building, and infrastructure characteristics leading to changes in water use, stormwater runoff, and wastewater generation rates. For example, the stormwater system becomes vulnerable when the removal of natural vegetation and trees during urbanization reduces interception capacity, thereby increasing the amount of rainfall reaching the ground surface. Moreover, the compaction of soil during construction (Pitt et al. 1999) and the introduction of impervious surfaces (Schueler 1994) reduce depression storage, infiltration, and groundwater recharge. These altered surface characteristics, combined with the introduction of efficient drainage systems, increase the drainage density of urban catchments, which decreases the travel time of overland flow to the drainage system and leads to flashier and higher-volume hydrologic responses and altered streamflow (Booth and Jackson 1997).

Population growth is another key stressor of urban water infrastructure systems contributing to vulnerability. Population growth is not only linked to changes in runoff but also causes larger scale increases in water demand and wastewater generation. It is the single most important factor used for water supply planning and is one that comes with substantial uncertainty. Projecting an estimated future metropolitan population is challenging in itself but is further complicated when projecting the impacts on water demand, surface runoff, and wastewater generation, thereby limiting the ability of utilities to precisely plan future system needs.

Another vulnerability of urban water infrastructure systems is aging and degradation of components. This vulnerability has been highlighted in numerous reports indicating the state of the infrastructure today and the projected state in the near future. Water losses of 10–20% are considered normal, and losses as much as 50% have been found in cities in the United States (US EPA 2009). Nationally, leaking pipes lose an estimated 7 billion gallons of drinking water each day (http://www.infrastructurereportcard.org/fact-sheet/drinking-water). Without proper corrective actions, this system vulnerability is expected to intensify and expand in the future.

The relative importance of each vulnerability-related stressor on future urban water infrastructure resiliency and sustainability is dependent on local conditions and future

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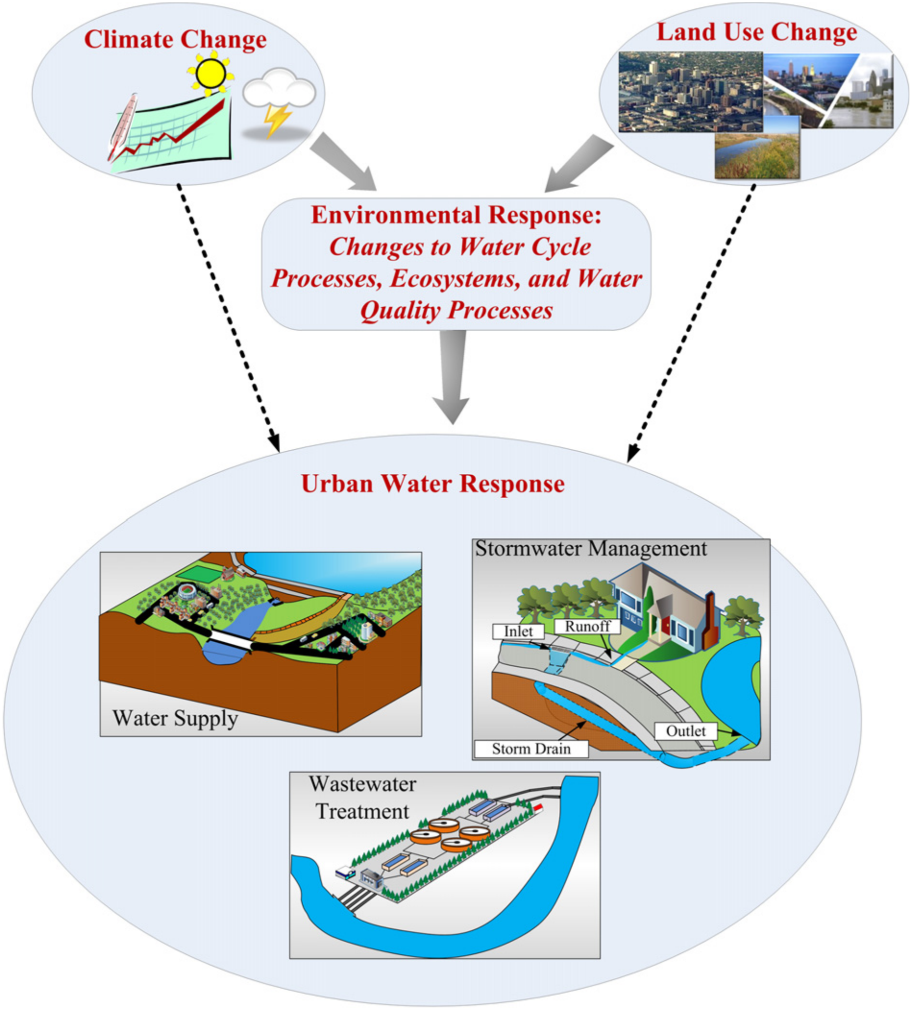

Figure 1 Pressures (e.g., climate, land use) impact environmental systems that in turn elicit a response within urban water infrastructure systems. Note: Possible feedbacks such as from urban water systems (e.g., reservoirs) and urbanization (e.g., urban heat island effect) to local climate are expected but not shown here.

trajectory of the influencing factors. A comprehensive water utility vulnerability assessment would address all of these factors and determine when and how to address them in a long-term adaptation plan. In-depth coverage of all of the factors is beyond the scope of this chapter. Rather, for consistency with the theme of the volume, the focus of this chapter is specifically on the vulnerabilities and adaptation measures to climate and a few key drivers of the water cycle.

Climate variability is generally defined as the variation in climate over space and time due to natural (e.g., fluctuations in ocean circulations, volcanic eruption) or anthropogenic (e.g., increased greenhouse gas emissions) influences (IPCC 2007a). Both natural and human-induced variability are relevant for this chapter because both affect the water cycle in similar ways that affect urban water infrastructure systems. Natural climate variability has been observed throughout history. Recently, the Intergovernmental Panel on Climate Change (IPCC) concluded that trends in global temperature over the past century could not be explained solely on the basis of the inherent variability of the climate system (IPCC 2001). Their assertion was that human-induced climate variability was also occurring. Natural climate variability is known to alter the water cycle (e.g., extended periods of reduced precipitation leading to drought), and human-induced climate effects would also have local and regional impacts on the water cycle, including altered evapotranspiration (ET), soil moisture, precipitation, groundwater recharge, and runoff (Allen and Ingram 2002; Milly et al. 2005; Schneider et al. 2007; Trapp et al. 2007).

Climate vulnerability of urban water infrastructure systems is defined as the state of being exposed to consequences and adversely affected from climate pressures on the water cycle, especially changes in precipitation intensity and frequency of extreme events, leading to a range of possible impacts that include increased runoff, reduced recharge, and higher flooding potential (IPCC 2007b). The resulting impacts on urban water infrastructure systems include physical damage, system failure, risk to population, and financial loss. The infrastructure components and entire systems are sensitive to resource changes on short (days), medium (season), and long (multiple decades) timescales.

Vulnerabilities to urban water infrastructure systems can be reduced by taking actions to mitigate or adapt to the human-induced and natural climate variability impacts. Adaptation is adjusting the built or natural system in response to climate variability impacts to reduce harm (Hamin and Gurran 2009). This chapter focuses on adaptation of urban water infrastructure systems; however, it is important to remember that mitigation and adaptation are interrelated and can either be a detriment or synergistic to one another (Buob and Stephan 2011).

The goals of this chapter are to summarize climate vulnerabilities and adaptation strategies of urban water infrastructure systems, identify climate vulnerabilities and adaptation potential of new green infrastructure and decentralization approaches, and highlight the importance of the interdependency of urban water infrastructure and energy requirements in relation to climate vulnerabilities and adaptation. The next section presents an overview of climate vulnerabilities and adaptation strategies of the three urban water infrastructure systems: water supply, stormwater management, and wastewater collection. Section 5.06.3 Toward Sustainable Urban Water Systems explores the climate vulnerabilities and adaptation potential of the new approaches of green infrastructure and decentralization, and identifies potential implications of climate vulnerabilities of urban water infrastructure systems for energy requirements.

5.06.2 Conventional Urban Water Infrastructure Systems

The pressures of climate on urban water infrastructure systems may influence their ability to meet former safety factors built into their designs for future demand requirements. Urban water systems are designed with a specified performance level, sometimes based on an adopted risk. For example, stormwater drainage systems are designed to infiltrate, convey, or capture a design rainfall event that historically has occurred on average once over a specified duration. Often the once-in-10-year event is selected for design of storm drainage networks with less frequent events (e.g., a once-in-50-year event) used for culverts, bridges, and other higher risk components. Water supply planning is based on population projections and assumed per capita or detailed demand estimates. The primary problem with past designs is that the basis of design used by engineers is becoming inadequate and may continue to be so as climate extremes intensify (Purkey et al. 2007). For example, water demands may increase in some places, and bridges, levees, and other water infrastructure designed to withstand the 100-year recurrence interval storm event may face more frequent high-intensity events. Indeed, these projected climate pressures have been observed in recent climate trends (Mount and Twiss 2005; Vicuña et al. 2006) as well as hazards and impact events. Additionally, other such climate-related pressures, as altered water cycle processes, change to air and water temperatures, and sea level rise (SLR) would affect urban water systems (Walsh et al. 2004; Barnett et al. 2005; IUCN 2008).

The general methodology of assessing climate vulnerabilities of urban water infrastructure systems can be broadly classified as 'top–down' or 'bottom–up' (Miller and Yates 2006; Usher 2010; Vogel and Smith 2010). The top–down approach refers to methods representing climate variability and change in the form of scenarios (e.g., increased/decreased precipitation, higher precipitation intensity, increased frequency of extreme events) using one or more of (but not limited to) the following types: (a) extrapolating from historical and paleoclimate precipitation records (Denault et al. 2007; Rosenberg et al. 2010), (b) synthesizing climate impacts using downscaled regional or global climate model outputs (for impacts on hydrology, see Maurer 2007; Beyene et al. 2010; Elsner et al. 2010; Maurer et al. 2010; for impacts on stormwater, see Semadeni-Davies et al. 2008; He et al. 2011), (c) simulating ensemble scenarios based on downscaled general circulation model (GCM) outputs (Rosenberg et al. 2010; for SLR, see Purvis et al. 2008), and (d) synthesis from literature reviews. Top–down approaches are model driven, as they may include application of GCMs and the integration of downscaled outputs with hydrologic or system models (Vogel and Smith 2010). The most common approach of top–down type methodologies for climate impacts is to use downscaled climate projections generated from GCM output in conjunction with hydrologic and/or water resource system models.

Bottom–up approaches, on the other hand, focus on local scales (e.g., urban drainage system of a city) and typically involve qualitative and quantitative assessment of system components to identify vulnerabilities. Most often, bottom–up approaches involve individuals with extensive knowledge of the natural and built systems that are being assessed. A usual process involves defining thresholds and performance criteria for the water infrastructure system components that represent the normal of expected operation without climate variation or change conditions, establishing climate variables of interest, determining system response to changes in important climate variables, and then developing and testing adaptation strategies (Freas et al. 2008). Alternatively, scenarios representing pressures on the system (e.g., altered precipitation intensity) that may or may not be predicted by downscaling analyses of model-projected climate have also been employed in sensitivity analyses that represent a hybrid of top–down and bottom–up approaches.

The focus on systems and components in a bottom–up approach permits a more comprehensive vulnerability assessment that extends beyond climate variability and change to include other key pressures (e.g., land use change, population growth, aging infrastructure, altered demands and water quality, socioeconomic changes) as well as the synergistic impacts of multiple pressures and of possible climatic conditions not included in the downscaled scenarios (Pielke et al. in press). The relative importance of climate vs. urban growth and other factors is dependent on site and conditions and is influenced by the scenario and modeling assumptions and local characteristics (Praskievicz and Chang 2009), which leads to the need for a bottom–up approach.

The use of the top–down approach is also limited by the uncertainty of data and the models used to drive the analysis. Uncertainty exists in projecting climate variability and change into the future and downscaling to the level necessary for water infrastructure assessment. Downscaling is especially

Table 1 Urban water infrastructure system pressure–response matrix

	Infrastructure impact/response		
Pressure (water cycle change)	*Water supply*[a]	*Stormwater*	*Wastewater*
Decreased precipitation	▼ Decreased water yield and recharge	▲▼ Decreased runoff volume; increased recurrence intervals[b,c]; increased pollutant concentrations	▲▼ Fewer CSO events; decreased streamflow leading to lower assimilative capacity
Increased precipitation	▲ Increased water yield and recharge	▼ Increased runoff volume[d]; increased peak flow; decreased recurrence intervals[b,c]; increased waterway erosion and flood risk; increased water turbidity[d]	▲▼ More CSO events; increased streamflow leading to greater assimilative capacity
Altered precipitation timing – Seasonal and interannual	▼ Water infrastructure designed based on supply–demand timing – negative impact on operations[e]	○ No significant impact	○ No significant impact
Increased precipitation intensity	▼ Increased flood risk to water supply infrastructure; decreased infiltration; increased contamination of water sources from runoff pollution[f]	▼ Decreased annual recurrence intervals[b]; increased peak flow, runoff,[d] erosion, flood risk, and turbidity[d]	▼ More CSO events; increased WWTP loading
Decreased precipitation intensity	○ No significant impact	▲ Decreased runoff; decreased pollutant loading	▲ Fewer CSO events
Increased ET	▼ Increased losses from reservoirs; increased salinization of water sources; decreased surface water and groundwater availability	▲ Increased removal of stored runoff in detention and retention basins[g]	○ No significant impact
Increased snow pack	▲ Increased water yield	▼ Increased melt runoff and flood risk	▲ Increased dilution of contaminant loads
Decreased snow pack	▼ Decreased water yield	▲ Decreased melt runoff and flood risk	▼ Decreased dilution of concentration loads
Earlier snowmelt	▼ Change to supply–demand timing challenges operations	○ No significant impact	○ No significant impact
Later snowmelt	▼ Change to supply–demand timing challenges operations	○ No significant impact	○ No significant impact

Increased streamflow	▲ Increased surface water availability	▲▼ Increased flood risk; increased dilution capacity	▲▼ Increased dilution of CSO loads; increased flood risk at outfall and backup into collection system
Decreased streamflow	▼ Decreased surface water availability	▲▼ Decreased flood risk; decreased dilution capacity	▲▼ Decreased dilution of CSO loads; decreased flood risk at outfall and backup into collection system
Raised groundwater table	○ No significant impact	▼ Waterlogging of green infrastructure[h]	▼ Increased exposure of sewer lines to groundwater – increased infiltration and inflow and contamination of groundwater
Lowered groundwater table	▼ Wells may run dry; increased pumping costs	○ No significant impact	○ No significant impact
Improved surface water quality	▲ Decreased treatment costs	▲ Decreased impact of pollutant loading	▲ Decreased impact of CSO loading
Degraded surface water quality	▼ Increased treatment costs	▼ Increased impact of pollution loading	▼ Increased impact of CSO pollution loading
Increased surface water temperature	▲▼ Decreased dissolved oxygen (DO), accelerated organic growth, algal blooms, altered chemical reactions, higher or lower treatment costs (depends on treatment process)	▼ Decreased DO affects certain aquatic species[i]; increased impact of pollution loading	▼ Increased impact of CSO pollution loading; altered discharge conditions for WWTPs (e.g., permits more restrictive)
Decreased surface water temperature	▲▼ Increased DO, decreased organic matter, altered chemical reactions; higher or lower treatment costs (depends on treatment process)	▲ Increased DO levels – reduced impact of pollution loading	▲ Decreased impact of CSO pollution loading; altered discharge conditions for WWTPs (i.e., permits less restrictive)
Improved groundwater quality	▲ Decreased treatment costs	○ No significant impact	○ No significant impact
Degraded groundwater quality	▼ Increased treatment costs	○ No significant impact	○ No significant impact
Sea level rise	▼ Saltwater intrusion into wells	▼ Increased flood risk[j]	▼ Increased flood risk for treatment facilities; outfall backup due to impacted hydraulics

[a] *AWWA Climate Change Committee (2011);*
[b] *Rosenberg et al. (2010);*
[c] *NRC (2011);*
[d] *He et al. (2011);*
[e] *O'Hara and Georgakakos (2006);*
[f] *Elliot et al. (2011);*
[g] *Shaw et al. (2005);*
[h] *ADB (2011);*
[i] *Debo and Reese (2003);*
[j] *Purvis et al. (2008);*

Note: A negative response indicated by a downward pointing arrow (▼) means the pressure is usually anticipated to have a negative effect. A typically anticipated positive response is symbolized by an upward pointing arrow (▲). A neutral response is symbolized by an open circle (○). If both a positive and negative are shown, it may have positive or negative depending on local conditions. A vulnerability may be likely if the response is negative.

problematic when trying to represent the temporal and spatial resolution of precipitation essential for water infrastructure analysis (Willems et al. 2011). Given the longevity of urban infrastructure, it is critical that decision making concerning water systems does not reinforce negative feedback in any part of the process (Lindley et al. 2006). In response to the advantages and disadvantages of both approaches, some water utilities have incorporated elements of both the top–down and bottom–up approaches into their assessment (US EPA 2010a).

Climate vulnerabilities to water supply, stormwater drainage, and wastewater collection systems have typically been assessed independently. Cities are responding to model-projected climate impacts by conducting vulnerability analyses for their water infrastructure systems and in some cases are embracing Integrated Resource Planning (IRP), which analyzes the impacts to all phases of the water supply and consumption cycle for the given system (Cromwell et al. 2007). In the United States, generalities of IPCC model-predicted climate impacts for future emission scenarios include the assumptions that coastal cities would be vulnerable to SLR and that Midwest and East Coast cities would be vulnerable to more intense storms. The West would be especially vulnerable to climate variation that could lead to water supply shortages and changes in snowmelt runoff timing, quality, and quantity. A recent report by the Natural Resources Defense Council (NRDC) highlights water-related climate risks in 12 US cities and describes the measured cities are taking to become more resilient (Dorfman et al. 2011).

Vulnerabilities of urban water systems vary in different countries based on expectations for reliability. This chapter focuses on the expected system reliability in the United States. Vulnerabilities can include environmental, social, political, economic, and security externalities, but this chapter focuses on climate. Generally, climate vulnerabilities of urban water systems fall into three categories: increased quantity (increased intensity and frequency of extreme events, SLR), decreased quantity (decreased water availability due to reduced precipitation, altered hydrologic response, and increased demand), and decreased quality. Each of these is considered in this chapter. The following subsections describe climate vulnerabilities and adaptation approaches of conventional (meaning those that are currently in widespread use in the United States) water supply, stormwater management, and wastewater collection systems.

5.06.2.1 Water Supply

Urban water supply infrastructure includes surface water diversions, wells, pumps, transmission pipes and canals, treatment and storage facilities, and distribution network elements. Sources include rivers, reservoirs, seawater, and groundwater. Climate variability leads to numerous physical changes to the water cycle that act as pressures to affect urban water infrastructure systems. Table 1 provides a comprehensive list of climate-related pressures on urban water infrastructure systems and indicates possible impacts and responses from the infrastructure systems.

As noted in Table 1, urban water supply has a propensity to be affected by pressures on both the supply and the demand sides, which exposes vulnerabilities. On the supply side, effects are anticipated regarding the quantity, timing, and quality of source water. On the demand side, effects are expected in use patterns in response to climate impacts. For example, alterations of temperature and relative humidity, growing season duration, and precipitation patterns may lead to changes in water demand for municipal landscape irrigation. IPCC model-based investigations of water supply impacts of climate predict reduced water availability and degraded quality (Gleick and Chalecki 1999; Gleick and Adams 2000).

Most studies of urban water supply system vulnerabilities to climate change are top–down as they have used scenarios from GCMs. In such a top–down approach, the climate change estimates of precipitation, temperature, and other meteorological parameters are used to drive a hydrologic model, which is then used to quantify changes in streamflow and reservoir water surface levels. A final stage of analysis that assesses impacts on municipal water supply systems is sometimes included (Wiley and Palmer 2008). The use of probability-based methods for assessing climate variability has also been employed and is used to provide risk-based outputs, including confidence levels (Maheepala and Perera 2003). However, application of probabilistic methods beyond research is limited, whereas the use of indicators defined specifically for climate impact assessment has proven worthwhile for addressing the problem quantitatively (Hurd et al. 1999).

In general, an altered hydrologic cycle from altered climate variability will result in modifications to the water yield (either surface water or groundwater resources) or alter the timing of the supply with respect to the demand (see, e.g., Barnett et al. 2005). The watersheds with the greatest vulnerability are those that are already stressed by existing conditions or face multiple stressors in addition to climate (Hurd et al. 1999). Vulnerability assessments carried out by water utilities have generally used external climate expertise for climate information and accounted for the uncertainty by employing a range of scenarios or models to test the robustness of the system to a subset of different possible future climate perturbations (US EPA 2010a).

Reservoirs are provided to equilibrate the timing of water supply, but the design and operation of the reservoir system may be vulnerable to climate. Studies of top–down model-predicted future climate impacts on water supply are often compounded by the added uncertainty of also projecting water demand. A study of reservoir storage capacity for the City of San Diego looked at both predictions of water demand and climate and determined that the addition of the human-induced climate forcings along with projected water demand would lead to greater costs for the city (O'Hara and Georgakakos 2006). Vano et al. (2010) studied the relative importance of population growth and model-predicted climate in the Puget Sound region.

Larger-scale impacts to water supply would occur from altered groundwater levels and SLR. Modified infiltration and recharge and increased withdrawals may lead to lowered groundwater levels. This would make existing pumping facilities ineffective or could lead to higher energy requirements for groundwater development (Larsen 2010).

Of all the climate effects on the water cycle listed in Table 1, SLR is the one that has gained the most consensus in terms of its response. SLR is predicted to occur with the claimed uncertainty mainly in the magnitude of the rise and the timing. Urban water infrastructure systems are vulnerable to SLR and the impacts may include saltwater intrusion in coastal wells.

Demand-side changes are also possible although not listed in Table 1. Climate-induced alterations of temperature and relative humidity, growing season duration, and precipitation patterns may lead to changes in water demand for municipal landscape irrigation and other outdoor uses. A study of water demand forecasts in three counties in Washington found the effects of the top–down predicted climate change, 50 years in the future, to be an average annual water demand increase of 5–12% (WSF 2009). However, projecting long-term changes to water demand are difficult since water demand generally increases with temperature and decreases with precipitation. Given the challenges of projecting demand-side changes, broader climate impact assessments of water supply infrastructure have been conducted within the analysis of the larger urban system impacts (e.g., for New York City, Rosenzweig et al. 2000).

Eight major water agencies in the United States formed the Water Utility Climate Alliance (WUCA) in February 2008 (WUCA 2011). Many water utilities now plan for and identify investments to mitigate and adapt their systems to climate variability and longer-term change based on tools including risk assessment and total water management (Freas et al. 2008). Effects on water utilities have been classified into several categories: water quantity, water quality, operational reliability, financial, and institutional (Water Research Foundation 2008; AWWA Climate Change Committee 2011). In general, adaptation objectives of water utilities are to diversify the water supply portfolio and seek low cost, 'no regrets' solutions (NDWAC 2010). No regrets adaptation strategies are those that "would generate net social and/or economic benefits irrespective of whether or not climate change occurs" (IPCC 2007c; Elliot et al. 2011). Costs to drinking water utilities in the United States for adaptation to possible climate conditions are estimated to be \$325–\$692 billion (CH2M Hill, AMWA, and NACWA 2009), although these costs are based primarily on 'hard-path' solutions.

Adaptation measures that are generally applied include conducting water resources planning using 'nonstationary' assumptions (Milly et al. 2008) and reducing demand. More detailed adaptation approaches and techniques are listed and described in Table 2 according to the pressure they are addressing. The most common structural adaptation measure typically considered is increasing storage capacity. Increasing storage is one of the 'no regrets' measures from the water supply perspective because it addresses a broad range of pressures related to climate variability and longer-term change, urbanization, and other factors. However, this route is expensive. Adjusting the operating plan of existing reservoirs has some potential benefits and is inexpensive, but increased storage is expected to have a greater impact across vulnerabilities. Research has shown that adding storage capacity to reservoirs will have larger benefits for adapting to increased demands vs. altered inflows and evaporation from climate.

It is important to note that the vulnerabilities and adaptation measures noted in Tables 1 and 2 assume that the paradigm for urban water management remains the same. However, alternative approaches to urban water management are being developed in response to wholesale changes in economy, energy, and urban development. Emerging changes to urban water infrastructure systems are highlighted in Section 5.06.3 of this chapter.

5.06.2.2 Stormwater Management and Flood Control

Stormwater management and flood control infrastructure may generally be classified (Gregory et al. 2005) as conveyance channels and conduits (e.g., streams, canals, ditches, culverts, pipes, streets), storage facilities (e.g., lakes, ponds, detention/retention basins), and other control structures (e.g., gates, locks, weirs, levees, berms, pump systems).

Climate vulnerabilities to stormwater and flood control infrastructure are related to (a) system design and (b) operation and maintenance (see Table 1). For design, engineering may have to consider the nonstationarity of historical precipitation used in the development of depth–duration–frequency curves and its impact on the selection of design storm magnitudes (NRC 2008; Rosenberg et al. 2010) in response to climate variability and longer-term change. From the operation and maintenance perspective, stormwater and floodplain managers may have to regularly monitor the system response to increased extreme events, high-intensity storms, and early spring flows. For example, increased erosion and sedimentation in urban water system streams and storm drains due to increased runoff would result in clogging of storm drains, leading to a backup of water and of culvert openings, backwater effects, and local flooding.

Climate pressures on urban drainage systems comprise (a) water quantity related impacts including increased runoff and flooding (Ashley et al. 2005; Milly et al. 2005), increased combined sewer overflow (CSO) occurrences (Liebl 2011), and increased erosion at sites with no drainage features and (b) water quality impacts from altered stormwater pollutant concentrations, increased erosion, increased turbidity, and elevated in-stream water temperatures (Debo and Reese 2003; Rosenberg et al. 2010; He et al. 2011). These effects of climate pressures vary with geographic region and level of urbanization. For example, Milly et al. (2005) presented climate model predictions of runoff increases of up to 40% by the year 2050 in the eastern equatorial Africa, high-latitude North America, and Eurasia, while parts of southern Africa, southern Europe, the Middle East, and the mid-latitude of North America were simulated to have runoff decreases of up to 30%. Dorfman et al. (2011) identified increased flooding as the most common climate risk in 12 US cities. Scientific studies that they reviewed indicated that rainfall intensity is forecast by the IPCC models to increase in many of their case study cities, leading to an increased incidence of flooding. This would in turn lead to an increased number of CSO events. The Great Lakes region, for example, is estimated to experience increased daily CSO discharges by up to two times a year, due to climate change according to US EPA (2008a).

Assuming, first, that current stormwater management practices continue unchanged into the future and, second, that a 30% shift in extreme precipitation quantiles would occur, it can be expected that quantity issues (e.g., flooding and combined sewer surcharging) would be twice as likely to occur

Table 2 Urban water infrastructure adaptation matrix

	Infrastructure adaptation		
Pressure (water cycle change)	*Water supply*	*Stormwater*	*Wastewater*
Decreased precipitation	$$ Reduce demand; create new water allocations; develop alternative sources and decentralize	$ Protect and reestablish wetlands to retain runoff and recharge groundwater[a]	○ Minimal adaptation necessary
Increased precipitation	○ Minimal adaptation necessary	$$$ Increase storage; install detention/retention facilities; improve channel stability; improve emergency response capacity; increase storm drain pipe size; install observational networks for flood forecasting[b]	$$$ Increase capacity for storage and treatment in combined sewer systems
Altered precipitation timing	$$$ Change reservoir operation; create new water allocation policy; reduce seasonal demand; increase storage capacity[c]	○ Minimal adaptation necessary	○ Minimal adaptation necessary
Increased precipitation intensity	○ Minimal adaptation necessary	$$$ Increase storage; improve emergency response capacity; install observational networks for flood forecasting[b]	$$$ Increase capacity for storage, surge protection, and treatment in combined sewer systems
Decreased precipitation intensity	○ Minimal adaptation necessary	○ Minimal adaptation necessary	○ Minimal adaptation necessary
Increased ET	$$ Alter storage infrastructure approach (e.g., aquifer storage and recovery)	○ Minimal adaptation necessary	○ Minimal adaptation necessary
Increased snow pack	○ Minimal adaptation necessary	$$ Increase storage and detention/retention facilities; fortify channels for flood control	○ Minimal adaptation necessary
Decreased snow pack	$$$ Increase storage capacity; create new water allocation policy; develop alternative sources of water supply; reduce demand	○ Minimal adaptation necessary	○ Minimal adaptation necessary
Earlier snowmelt	$$ Increase storage capacity; develop alternative sources of water supply; reduce or change timing of demand	$ Implement integrated stormwater/flood risk management studies[d]; improve emergency response capacity	○ Minimal adaptation necessary
Later snowmelt	○ Minimal adaptation necessary	○ Minimal adaptation necessary	○ Minimal adaptation necessary

Increased streamflow	○ Minimal adaptation necessary	$$ Implement integrated stormwater/flood risk management studies[d]; minimize impervious surfaces; encourage riparian buffer zones along waterways[a]; install observational networks for flood forecasting[b]	$ Elevate or protect WWTP discharge outlet location from backflow or flooding
Decreased streamflow	$$$ Modify intake structures; reduce demand; develop alternative sources of water supply	$$ Install stormwater quality control devices	$$ CSO discharges have greater harm – need to increase controls and/or treatment in Total Maximum Daily Load (TMDL) locations
Raised groundwater table	○ Minimal adaptation necessary	$$ Map hydric soils to select locations for new drainage designs; prevent stormwater leaks[e]	$$ Increased repair or replacement of wastewater mains
Lowered groundwater table	$$ Drill deeper wells; develop alternative sources	○ Minimal adaptation necessary	○ Minimal adaptation necessary
Improved surface water quality	○ Minimal adaptation necessary	○ Minimal adaptation necessary	○ Minimal adaptation necessary
Degraded surface water quality	$$$ Introduce new treatment; develop new sources; revise standards	$$ Disconnect stormwater inputs; educate homeowners, farmers[f,g]; install source control best management practices (BMP)[h]	$$ Depends on local and National Pollutant Discharge Elimination System (NPDES) permit conditions; CSO discharges have greater harm—need to increase controls and/or treatment in TMDL locations
Increased surface water temperature	○ Minimal adaptation necessary	$ LID or GI, in place of traditional detention/retention	○ Minimal adaptation necessary
Decreased surface water temperature	○ Minimal adaptation necessary	○ Minimal adaptation necessary	○ Minimal adaptation necessary
Improved groundwater quality	○ Minimal adaptation necessary	○ Minimal adaptation necessary	○ Minimal adaptation necessary
Degraded groundwater quality	$$$ Introduce new treatment; develop new sources	$ Educate homeowners, farmers[f,g]	○ Minimal adaptation necessary
Sea level rise	$$$ Introduce new treatment; develop new sources	$$$ Install sea walls; install pumps; integrated coastal flood risk management[e,f]	$$$ Impacts outfalls – may require pumping; treatment facilities may need to be moved or protected from inundation

[a] *McCormick (2011);*
[b] *CA DWR (2008);*
[c] *O'Hara and Georgakakos (2006);*
[d] *USACE (2011);*
[e] *Liebl (2011);*
[f] *Purvis et al. (2008);*
[g] *WICCI (2011);*
[h] *MOE (2010);*

Note: Shown are possible adaptation measures for urban water infrastructure systems and the relative cost (○ indicates negligible cost; $ indicates low cost, $$ indicates moderate cost, and $$$ indicates high cost).

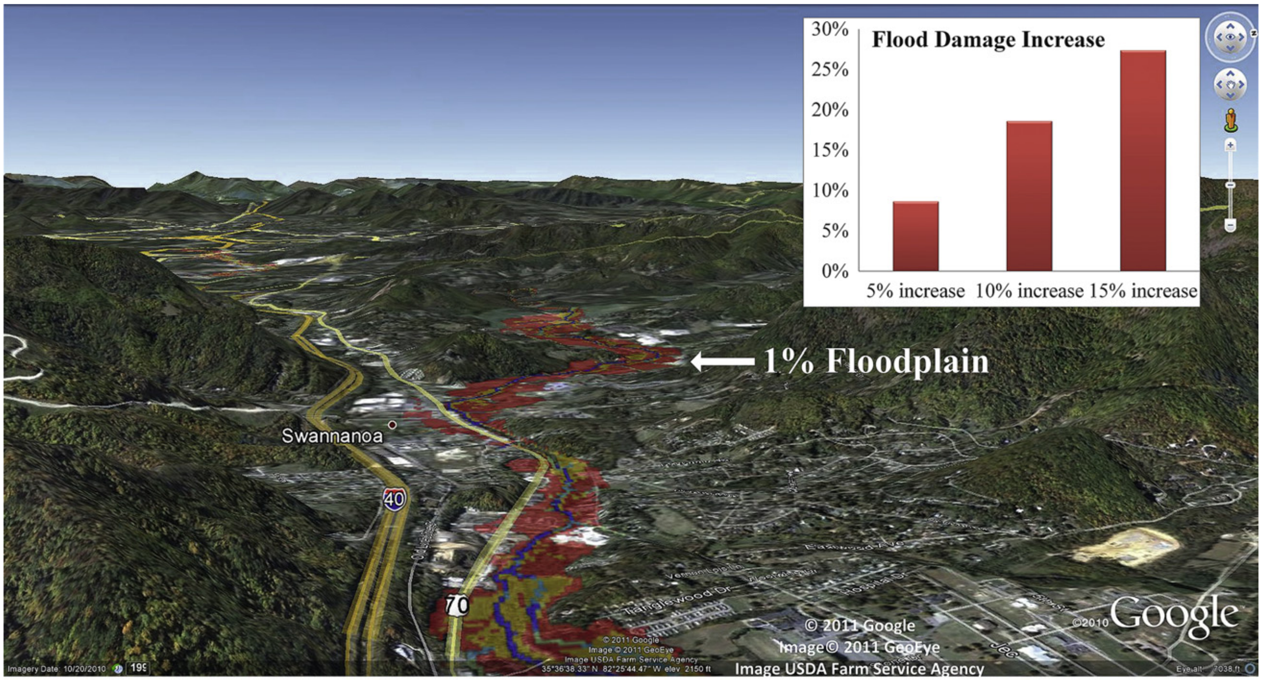

Figure 2 Sensitivity of flood damage increases for reach of the Swannanoa River. The colored area encompassing the river represents the flood inundation extent from the 1% event (i.e., 1% floodplain).

when compared to the climate for which the water systems were built (Willems and Vrac 2011 provides an example for Belgium). A direct vulnerability from these responses is on the increasing economic burden from flooding. For example, an analysis in Swannanoa, North Carolina, indicates the flood damage increases may not be linear with flow rate increases. A 15% increase in flow in the Swannanoa River was discovered to produce a 25% increase in flood damages using a calibrated HEC-RAS model provided by the North Carolina Floodplain Mapping Program (G&O 2007) and flood damage framework of Kalyanapu (2011) (Figure 2). While the majority of the stormwater management and flood control infrastructure is designed without considering a changing climate, it is important to consider how to realistically include the pressures of climate variability and long-term change on stormwater and flood control planning, design, and operation.

Climate vulnerabilities and adaptation strategies are unique to a community, county, state, or region. Vulnerability assessment and adaptation require interdisciplinary participation from stakeholders, politicians, city planners, green area managers, hydrologists, and economists (Arnbjerg-Nielsen and Fleischer 2009). These strategies vary widely based on vulnerability assessments for regions, with different climate and topographic characteristics (e.g., coastal vs. inland, hilly regions vs. plains, arid vs. wet regions), as they are directly related to inherent climate vulnerabilities. Adaptation strategies for stormwater management and flood control may generally include (Montalto et al. 2007; Hallegatte et al. 2010; MOE 2010; Pyke et al. 2011; USACE 2011; WICCI 2011): applying hydrologic and hydraulic models to simulate extreme events; regularly testing drainage system performance; retrofitting existing stormwater storage facilities to capture higher runoff volumes; stormwater harvesting and reuse; implementing source control best management practices (BMPs); identifying possible upgrades to appropriate green infrastructure; educating homeowners about water conservation; strengthening flood control structures to ensure safe passage of higher flood waves; addressing nonstationarity of historical precipitation estimates in hydrologic and hydraulic design of infrastructure; taking an integrated flood-risk management approach; considering both structural and nonstructural flood control alternatives; implementing feasible, cost-effective green infrastructure (see Section 5.06.3.1 of this chapter); improving vulnerability assessments (including bottom–up approaches) at the project level; and developing quantifiable measures to evaluate adaptation effectiveness. Table 2 summarizes some possible adaptation options to stormwater and flood infrastructure corresponding to various climate pressures on water cycle changes. It is important to note that the adaptation strategies may have variable effects on the urban water system vulnerabilities since performance may vary at different spatial scales (e.g., local subcatchment vs. regional river basin scale).

5.06.2.3 Wastewater

Wastewater collection and treatment infrastructure includes septic tanks, sewer pipes, lift stations, treatment facilities, storage tanks, and other appurtenances (US EPA 2012). Wastewater in developed areas is managed using decentralized septic systems or centralized sewers and treatment facilities depending on density, both of which have been identified to possess numerous vulnerabilities to natural and anthropogenic climate variability longer-term change. In the United States, the need to manage sewer flows has been met via conveyance systems, which historically have been categorized as either sanitary sewer systems (SSSs) or combined sewer systems (CSSs) (Marsalek et al. 1993; Burian et al. 1999, 2000; US EPA 2004, 2012). According to the Clean Water Act, CSSs convey domestic, commercial, and industrial wastewater and stormwater runoff through a single pipe system, whereas SSSs convey domestic, commercial, and industrial wastewater, with limited amounts of groundwater and stormwater, through a single pipe system (US EPA 2004). Application and management of these systems has mostly been based on analysis of stable climatic and stationary hydrologic conditions (Kundzewicz et al. 2008; West et al. 2009). Design of CSSs allowed for proper management of dry weather flows, while wet weather flows added strain to the flow-handling capacity of the system, thereby leading to CSO events. As of 2004, there were 746 US communities with an estimated total annual CSO volume exceeding 850 billion gallons of untreated CSS water released to receiving water bodies. Alternatively, while less common, SSSs are estimated to release between 3 and 10 billion gallons of untreated water annually via sanitary sewer overflow (SSO) events (US EPA 2004).

Water-carriage sewage systems are the predominant paradigm used in US cities. They require copious amounts of water to collect and transport human waste to treatment facilities. Water demand for toilet flushing is among the highest percentage of residential per capita water use (e.g., 27% of total indoor water use in Utah, according to Utah DWR 2011). Climate vulnerability to this system is very high if water availability is changed by climate variability or long-term change.

The effect of future climate on the sewer conveyance systems results in a greater prevalence of wet weather events resulting in CSOs, since SSSs are less affected by infiltration and stormwater increases. This leads to enhanced wastewater system vulnerabilities, such as increased hydraulic loadings to wastewater treatment plants (WWTPs) and increased concentrations of pollutants (i.e., well-removable sewage-based contaminants and nutrients during wet weather events) released to the environment (Niemczynowicz 1989; Polaskova et al. 2006; Kundzewicz et al. 2008; Semadeni-Davies et al. 2008; Weyrauch et al. 2010). This leads to reduced treatment performance of WWTPs, adds to both capital and operating costs, and increases the amount of pollutants discharged to the receiving environment.

WWTPs located in coastal areas would be exposed to SLR and therefore would be subject to inundation and damages (Kirshen et al. 2008a). SLR would create significant problems with respect to discharge and backup into gravity-fed sewer lines that outfall to the sea. The consequence is expected to be decreased carrying capacity and a higher potential for CSO events (Burton et al. 2005). This will require substantial infrastructure modifications to provide unimpeded discharge of treated effluent. Similarly, an increase in stream levels from greater amounts or intensities of precipitation events would increase the potential for infrastructure damages and flooding of prone areas. Dependent upon the magnitude of changing groundwater levels, wastewater systems could experience either a gain or a loss of conveyance volumes, leading to increased dilution and infrastructure damages due to the presence of surrounding water or increased concentrations and potential groundwater contamination, respectively (Foster 1990).

Hydrologic responses affect both the quantity and quality of a watershed's water resources and have been found not to be limited to only small receiving bodies, as was the traditional focus of CSO studies (Semadeni-Davies 2004; Weyrauch et al. 2010). More importantly, regardless of any alterations in climate, the increasing growth and concentration of human population within urban centers and smaller cities alone will lead to greater demands and strains applied to the wastewater system (Rosemarin 2005). Thus, it is imperative for local governments to carry out vulnerability assessments that take into account climatic changes and also include other factors affecting an area's water resources (US EPA 2010a).

As described in **Table 2**, adaptation measures seek to increase storage capacity in CSSs to prevent or reduce CSO events and to implement full-cost pricing of water resources via analysis of the economics of the urban water life cycle, while others aim at increasing ecological sanitation measures and highlighting greater efficiency in water use, such as the EcoSanRes Programme (Commonwealth of Australia 1997; Kirshen et al. 2008b; Rosemarin 2005). In flood-risk coastal zones, either flood protection may be required at treatment facilities and their outfall locations or the facilities may need to be moved altogether. Other adaptive measures include recycling and reuse of treated wastewater, movement toward an SSS, use of decentralized alternative sanitation systems (see Section 5.06.3.2), improving treatment capacity to meet increased volume (e.g., provision of increased storage) or contaminant concentrations (e.g., enhanced treatment), and expanding pump system capacity to meet increased hydraulic head caused by storm surges raising the discharge outlet water surface elevation (Kundzewicz et al. 2008; Bates et al. 2008). However, successful adaptation of stormwater management (i.e., integrated urban water management, or IUWM) to climate should decrease the occurrence and magnitude of wastewater vulnerabilities, especially under a CSS (Mitchell 2006).

5.06.3 Toward Sustainable Urban Water Systems

New approaches that seek to achieve sustainability of urban water infrastructure systems have emerged in the past two decades. Approaches are now applying the Triple Bottom Line framework and life cycle analysis to consider solutions that address economic, environmental, and social aspects of projects and take a cradle-to-grave perspective. Addressing climate variability and possible long-term change and other vulnerabilities is important for providing a resilient and sustainable infrastructure system.

One of the important paradigm shifts in managing stormwater sustainably is the concept of low-impact development (LID) introduced in the late 1990s in the United States (Prince George's County 2000). LID concepts encourage introduction of green infrastructure (GI) practices that help achieve the goal of restoring the natural hydrologic cycle. In Section 5.06.3.1, the role of GI in climate vulnerability and adaptability of urban water infrastructure systems is presented. Another new approach to urban water management is decentralization. The action of taking management of urban water away from centralized treatment, distribution, and collection systems has emerged as potentially a more sustainable approach.

Decentralized approaches are briefly highlighted in Section 5.06.3.2. Lastly, in Section 5.06.3.3 we consider the important interconnection of energy requirements with urban water infrastructure systems and how this interconnectedness provides the opportunity to improve sustainability.

5.06.3.1 Green Infrastructure

The US EPA defines LID as a method of land development (or redevelopment) that functions in tandem with nature in order to provide source control, or as close to the source as possible, of stormwater. Principles behind LID include mimicking and preserving natural features of the landscape, minimization of impervious areas that contribute to water quantity and quality issues, and providing an interactive and aesthetically pleasing environment for users. By harmonizing these standards, LID has the ability to possess multiple values, encompassing the three spheres of sustainability: economic, social, and environmental (US EPA 2011c). GI, in the context of LID, is defined as any system or practice that uses or mimics natural processes in order to infiltrate, evapotranspirate, or reuse stormwater or runoff on the site where it is generated (US EPA 2011c). Examples of GI practices include, but are not limited to, bioretention gardens, permeable pavement, grassed swales, green rooftops, and constructed wetlands. GI practices have important influences on the urban water cycle that lead to benefits that improve urban water infrastructure sustainability (Burian and Pomeroy 2010).

Vulnerabilities of GI to climate conditions are explained by focusing on the underlying general stormwater management methods provided, such as vegetative, subsurface storage, and surface storage (**Table 3**). Acting upon these methods, any alterations in climate will ultimately affect the quality and quantity issues of stormwater in urban areas. In addition, depending upon the direction and magnitude of climate variability and long-term change and the configuration of the greater, interconnected system of LID, each GI method may experience a range of vulnerabilities. Refer to **Tables 3 and 4** for examples of potential vulnerabilities.

Since the health of vegetation is subject to climate conditions, practices employing this method are directly sensitive to climate, possibly resulting in reduced plant efficiency and plant disease and death. Indirect vulnerabilities include the introduction of nonnative species or weeds, leading to a reduction of both native species and plant diversity (Hauser et al. 2009). Indirect vulnerabilities also include the health and diversity of macroinvertebrates, such economic requirements as supplemental irrigation during times of drought, and groundwater recharge (Bisgrove and Hadley 2002; Green et al. 2007a; US EPA 2010c).

Table 3 Green infrastructure methods (for use with **Table 4**)

Green infrastructure practice	*Methods employed*
Bioretention	Vegetative, subsurface storage, surface storage
Permeable pavement	Subsurface storage
Grassed swale	Vegetative, subsurface storage, surface storage
Green rooftop	Vegetative, subsurface storage
Constructed wetlands	Vegetative, surface storage

Subsurface storage may be vulnerable to climate variability and long-term change due to its potential for slow recharge rates, groundwater contamination (i.e., contaminants and salinization), and changing water levels (Sugita and Nakane 2007). Once polluted, groundwater may prove difficult to remediate (U.S. EPA 1992). Groundwater recharge may also be affected, either seasonally or as a result of increasing surface temperatures (van Roosmalen et al. 2007; Taniguchi et al. 2007). Other vulnerabilities include a greater potential for inundation of the storage layer, thereby reducing the unit's capacity for stormwater management and, with a higher contaminant load being applied to the unit, the in situ soil characteristics and surrounding groundwater may be affected.

Surface storage may be vulnerable as a result of higher evaporative losses and therefore be associated with salinity issues. In addition, the areal footprint required by surface storage methods may exceed that which is available for proper stormwater management (Keller et al. 2000). Other vulnerabilities include a potential for reduced capacity due to either increased precipitation or elevated groundwater levels, which could lead to a longer duration of erosive discharge flows (determined by the outlet design) to receiving bodies, a higher possibility for vectors, and amplification of contaminant pulses in receiving water bodies (Kaushal et al. 2010).

Similarly, GI adaptations to climate variability can be elucidated by referencing the same generic stormwater management methods provided (**Table 4**). Vegetation provides relief of the urban heat island effect by increasing permeable green space and facilitating ET (US EPA 2008b). Additionally, plants provide water quality treatment and a slowing of runoff via increased roughness, as compared to traditional impervious surfaces such as concrete or asphalt. Subsurface storage offers municipalities with a reliable means of water management, including storage with minor evaporative losses and some water quality benefits. Surface storage provides adaptation to climate change in that it aids in dampening, via distributed collection, urban hydrologic responses, such as flooding and peak flow rates (Keller et al. 2000; US EPA 2011b).

However, more information regarding both the individual scale and greater network of LID practices is required, which should lead to a suite of adaptation strategies that will permit the greatest amount of flexibility when anticipating future climate scenarios, regardless of the direction that climate change occurs (Vorosmarty et al. 2000; Sophocleous 2004; Fletcher et al. 2007; Green et al. 2007b). In doing so, this will lead to different metrics of system performance, exceedances, and consequences (Berggren 2008), thereby bringing to light the adaptation potential of GI, which is high due to flexibility of site scale design and 'retrofitability' within the urban environment. Large-scale stormwater management structures will be more difficult and costly to implement in a retrofit situation. Additionally, just as under historical climate conditions, such stormwater management techniques are dependent upon the local and antecedent conditions and require consistent maintenance, which is a key to the success or failure of both the individual and overall local government management network (Claytor 2003). Sustainability requires active participation by

Table 4 Green infrastructure method responses to climate vulnerabilities and adaptation potential

Method	*Pressure*	*Vulnerabilities to climate*	*Adaptations to climate*
Vegetative	Increased precipitation	May cause inundation; plant disease or death	Slows and intercepts runoff, thereby dampening urban hydrological response; reduction in flood and landslide potentials; dampen the urban heat island effect; decreased in-stream erosive forces and turbidity
	Decreased precipitation	May require supplemental irrigation; plant death	Removal of higher pollutant concentration loads from applied runoff
	Altered precipitation timing	May damage cover (shorter time to peak); may inundate (longer time to peak)	Can dampen result (e.g., flooding) of increased magnitude of urban hydrologic response; decreased in-stream erosive forces and turbidity
	Increased precipitation intensity	May damage cover	Slows and intercepts runoff, thereby dampening urban hydrological response; reduction in flood and landslide potentials; dampen the urban heat island effect; decreased in-stream erosive forces and turbidity
	Decreased precipitation intensity	None	Removal of higher pollutant concentration loads from applied runoff
	Raised groundwater table	May cause inundation of root zone or above; plant disease or death	None
	Lowered groundwater table	May require supplemental irrigation; plant death	Increase storage capacity; increase infiltration ability
	Increased ET	May require supplemental irrigation; plant death	Enhance vegetative ability to use water; enhance ability to infiltrate applied runoff; dampen the urban heat island effect
	Sea level rise	May cause inundation; may cause unwanted salt infiltration; plant death	Defense against saltwater intrusion's effect on vegetation
Subsurface storage	Increased precipitation	May decrease efficiency or capacity; groundwater mounding potential; freeze–thaw potential near surface	Dampen urban hydrologic response (e.g., flooding and increased in-stream flows); decrease in-stream erosive forces and turbidity
	Decreased precipitation	None	Increase storage capacity for precipitation events
	Altered precipitation timing	May inundate unit if flashier event	Depends on local conditions; increase storage capacity if less flashy of an event
	Increased precipitation intensity	May decrease efficiency or capacity; groundwater mounding potential; freeze–thaw potential near surface	Dampen urban hydrologic response (e.g., flooding and increased in-stream flows)
	Decreased precipitation intensity	None	Removal of higher pollutant concentration loads, some water quality benefits
	Raised groundwater table	May reduce capacity and efficiency; groundwater mounding potential; freeze–thaw potential near surface	None
	Lowered groundwater table	None	Provide areas for direct groundwater replenishment
	Increased ET	None	Less evaporative loss, compared with surface storage; dampen urban heat island effect (minor)
	Sea level rise	May cause destruction or inundation	Provide specific zones of porous media, facilitating infiltration of seawater
Surface storage	Increased precipitation	May inundate, causing overflow; increased vector potential (e.g., standing water as breeding ground for mosquitoes)	Intercept runoff; dampen urban hydrologic response; dampen urban heat island effect; decrease in-stream erosive forces and turbidity
	Decreased precipitation	None	Increase storage capacity for future events
	Altered precipitation timing	May inundate, causing overflow or damage if flashier event	May increase storage capacity if less flashy
	Increased precipitation intensity	May inundate, causing overflow	Dampen urban hydrologic response; decrease in-stream erosive forces and turbidity
	Decreased precipitation intensity	May increase contaminant concentration in applied runoff	Collect and provide settling of contaminant load, prior to discharge or infiltration (some treatment)
	Raised groundwater table	May inhibit infiltration capacity, causing reduction in storage and potential for overflow	Provide specified zones of ponding of water
	Lowered groundwater table	None	Increase ability to infiltrate, thereby allowing greater storage capacity; treatment via infiltration and settling
	Increased ET	May increase susceptibility to evaporation, leading to contaminant issues (e.g., salinity)	Dampen urban heat island effect
	Sea level rise	May cause destruction or inundation; may increase contamination (e.g., salinity)	Provide specified zones for management of seawater, if designed specifically with higher salinity loads in mind

both citizenry and government, with education, coordination, and oversight provided by maintenance plans and vulnerability assessments.

5.06.3.2 Decentralization

The design of water, stormwater, and wastewater infrastructure has evolved with established, although not always accurate, understanding of flood control, disease, and public health (Burian et al. 1999, 2000). As an outcome of its historical development, urban water infrastructure designs are predominantly based on a centralized concept and the use of one quality of water for many (and in some cases, all) uses. The centralized approach is giving way under certain circumstances to decentralized approaches to meet water supply, stormwater management, and wastewater management needs (Maher and Lustig 2003). This subsection provides a brief review of decentralization approaches.

In contrast to centralized stormwater management, the decentralizing action of minimizing a directly connected impervious area can reduce runoff volumes, rates, pollutants, and cost for drainage infrastructure by directing the runoff generated by an impervious surface to a pervious area (Guo 2008). This process employs practices such as LID, Water Sensitive Urban Design (WSUD), and GI, which treat stormwater as a resource (Maher and Lustig 2003). In addition, application of distributed, or decentralized, management approaches to reconnect the hydrologic cycle and provide storage or additional treatment (Huber et al. 2006) has the potential to reduce downstream infrastructure capacity needs (Guo 2008).

Such approaches combine "a set of practices that mimic natural processes to retain and use stormwater…[by] promoting infiltration, evapotranspiration, and harvesting throughout the landscape" (US EPA 2010b). Common applications in water-abundant regions such as the northeast and northwest United States, these practices hold potential for greater research and use in arid and semi-arid regions as well, such as in the western and southwestern United States.

The cumulative benefits of widespread, decentralized stormwater management practices have the capacity to accumulate over time, incorporating both large- and small-scale actions, and contribute to the overall resource sustainability of regions. For instance, the preservation and restoration of natural landscape features (such as forests, floodplains, and wetlands in urban environments) provide large-scale protection to ecologically sensitive areas, as well as the application of numerous distributed site-specific practices (US EPA 2011c). In cases where LID is applied, significant savings are realized due to reduced costs for site grading and preparation, stormwater infrastructure, site paving, and landscaping (US EPA 2007). Other benefits include a reduction or delay in stormwater runoff volumes, improved groundwater recharge, a reduction in sewer overflows, increased potential for carbon sequestration, mitigation of the urban heat island effect, a reduction in energy demands, improved air quality, enhanced biota health and habitat, additional recreational space, reduction in stormwater pollutants, improved human health, and increased land values (US EPA 2011c). These are clear opportunities to reduce vulnerabilities, mitigate climate change, and provide for adaptation benefits of urban water infrastructure systems. Life-cycle assessments of GI have shown such approaches reduce greenhouse gas (GHG) emissions, environmental impacts, life-cycle cost, and in general provide a more sustainable option when assessed by the Triple Bottom Line compared to traditional solutions (Spatari et al. 2011).

However, despite the benefits, decentralization of stormwater management could make it harder to ensure that the owners operate and maintain the practices properly (Maher and Lustig 2003). To address this concern, we believe a system of oversight, or checks and balances, could be implemented and adapted by communities, placing stakeholders in charge of construction and maintenance. This would maintain both efficiency and reliability of the units while improving the education and connection of residents to the hydrologic cycle within the greater watershed.

Further research is also needed to quantify the environmental benefits that can be achieved through the use of LID techniques and the costs that can be avoided (US EPA 2007). It is important to reduce these costs, since they can amount to more than $400 billion for capital investment and capitalized costs of $540 billion for operation and maintenance of stormwater control facilities in the United States (Huber et al. 2006). Additionally, more research is needed to monetize the cost reductions that can be achieved through improved environmental performance, reductions in long-term operation and maintenance costs, and reductions in the life cycle costs of replacing or rehabilitating infrastructure (US EPA 2007), which goes part and parcel with the environmental and biological integrity of urban and urban-associated areas.

Although the decentralization practice of rainwater harvesting (RWH) possesses the ability to alleviate the water quantity and quality problems associated with climate variability and longer-term change, the overapplication of such units has the potential of being a detriment to receiving water health (Coombes and Barry 2007; Fletcher et al. 2007). In a study modeling the impacts of RWH across differing levels of urbanization (i.e., imperviousness) for the Australian cities of Brisbane and Melbourne, researchers determined that both quantity and quality indicators [i.e., total runoff, frequency of runoff, total suspended solids (TSS), total phosphorous (TP), and total nitrogen (TN)] could be returned to predeveloped levels; however, where higher rainfall intensities were experienced, this led to less reliability of RWH to alleviate quantity issues. Overextraction of precipitation was simulated for Melbourne under varying combinations of development and demand, and the results posed the scenario of starving receiving bodies of the required environmental flows.

In addition to decentralization of stormwater and water supply, alternative decentralized sanitation approaches are being introduced. Examples include dry sanitation systems such as composting toilets and no mix toilets (Gajurel et al. 2003; Tonner-Klank et al. 2007; Hotta and Funamizu 2009; Rossi et al. 2009). These approaches have limited vulnerability to climate, yet provide a measure to adapt to reduced water supply challenges facing water-carriage sewer systems. Another decentralization measure that provides an adaptation of the sanitation and water supply system is gray-water reuse (Goddard 2006; Memon et al. 2007) and treatment of wastewater onsite (Meuler et al. 2008). Both measures would reduce a vulnerability to limited water supply and provide a reduced demand on the wastewater collection and treatment system.

5.06.3.3 Energy Interdependency

It has become apparent that climate vulnerabilities and adaptation related to urban water infrastructure systems must consider energy requirement. A 2005 study by the California Energy Commission (CEC) found that the energy requirement for water-related services was about 19% of the total electricity demand and approximately 34% of all natural gas demand for the state (CEC 2005). The study received much publicity after its release when water managers realized the implications of such a high-energy demand and began to review their own water supply and energy needs. As a follow-up to the report, Stokes and Horvath (2009) reviewed the energy required to meet California's projected water demand in 2030 using a broad range of potential water sources—from imported surface water to recycled water to desalinated sources. They found that the method chosen to meet California's increasing water demand had a tremendous impact on how much energy might be used as well. Specifically, their study indicated that California's energy use in the future could increase from the current percentage of 19% of its energy budget to up to 52% if planners chose more energy-intensive methods such as desalination. Their study also indicated that surface water imported to the state is one of the least energy-intensive sources of water. However, this method of water provision is also likely the most vulnerable to climate variability and longer-term change. In a scenario that includes declining precipitation and more erratic surface water hydrology, water managers may opt to replace surface water sources with more energy-intensive ones, such as deep groundwater or desalination, which in turn would increase emissions and exacerbate the condition (CEC 2005). This, combined with existing overdraft practices within some water systems, would create a 'lose–lose' situation wherein the resource becomes depleted and the cost to lift more water to the surface rises prohibitively (CEC 2006). The overarching message from the Stokes study was simply that the choices made by water planners and decision makers today could propagate into the future and have unintended and possibly negative effects. It also pointed to some of the other drivers – in this case, a rapidly growing water demand – aside from climate variables that could introduce shortages to urban water systems and result in conflict (Zimmerman et al. 2008).

A study similar to the CEC's report concerning water services was conducted for Utah by Larsen and Burian (2011), which estimated the percentage of Utah's total energy budget used for water services to be approximately 7%. This study highlighted some of the geographic advantages states may have that can facilitate water supply services. For example, the snow pack and reservoir storage of water supplies in the mountains adjacent to the Salt Lake City metropolitan area provide a pressurized supply of high-quality water, requiring very little energy to convey or to treat. However, climate variability and longer-term change may lessen the availability of surface water supply with many attendant drawbacks mentioned above. Water agencies that are already heavily reliant on, or are currently mining, their aquifer resources may adjust to surface supply shortage by accelerating those withdrawals and see their energy costs rise in tandem. Groundwater sources require a great deal of energy to lift water to the surface, and the amount of energy required increases as the water table drops. Secondary impacts derived from the necessity of increased pumping, treatment, and pressurization include the cost of additional power generation infrastructure, the cost of new dams or storage infrastructure to capture more runoff, and the attendant GHG emissions that accompany more energy-intensive processes and facilities. Depending on the energy mix of the region (coal is the primary component of Utah's energy portfolio), added contributions of GHGs and other harmful pollutants could be substantial. And finally, as pumping is also one of the primary costs to water utilities, substantial increases in groundwater withdrawals could have an immediate impact on the financial standing of some districts.

The implications of declining surface water supply in terms of energy requirement were investigated and quantified for a case study water system in Utah (Larsen and Burian 2011). The Jordan Valley Water Conservancy District (JVWCD) is a large wholesale and retail water system situated in the southwestern quadrant of the Salt Lake Valley. Smaller member-agencies are comprised of local governments and other water district customers, which in turn supply and sell water directly to retail customers. In total, JVWCD and its member agencies serve more than half of the population living in the Salt Lake Valley. Their water supply sources include snowmelt runoff – imported via tunnels, diversions, and canals over 480 km – from the high Uinta Mountains to the Salt Lake Valley. They also supplement this supply with an array of groundwater wells, especially over the summer months when demand for outdoor irrigation water is higher. Retail agencies purchase water from JVWCD but may also supplement these purchases with groundwater wells within their district boundaries or from other sources. Using an energy estimation tool for water services created by Larsen (2010), an estimate of JVWCD energy requirement for water services under a climate change scenario was evaluated. The model assumed that groundwater supplies were adequate and a reduction in available surface water supply would be compensated for with an increase in groundwater withdrawals. Groundwater withdrawal estimates were made based on historic surface water availability for the district during and after a prolonged drought, groundwater withdrawals, and other climate variables (a reasonable assumption for the JVWCD and other water providers in the American West). Figure 3 is a graph of the estimated increase in energy requirement from additional compensatory groundwater pumping for JVWCD. The figure shows an estimated increase in energy for a low- and a high-energy-use range with incremental reductions in available surface water. A 20% reduction in surface water is estimated to result in 3.3 million kWh per year increase in energy consumption due to additional groundwater pumping, while a 35% reduction amounts to approximately 5.8 million additional kWh per year for the low-range system.

JVWCD is one of the larger urban water agencies that are situated to take advantage of snow pack runoff and gravity-fed network pressurization in Utah. Other agencies either purchase from water wholesalers or rely more heavily on groundwater. For example, Salt Lake City Public Utilities' water supply sources vary from year to year, but it relies significantly on

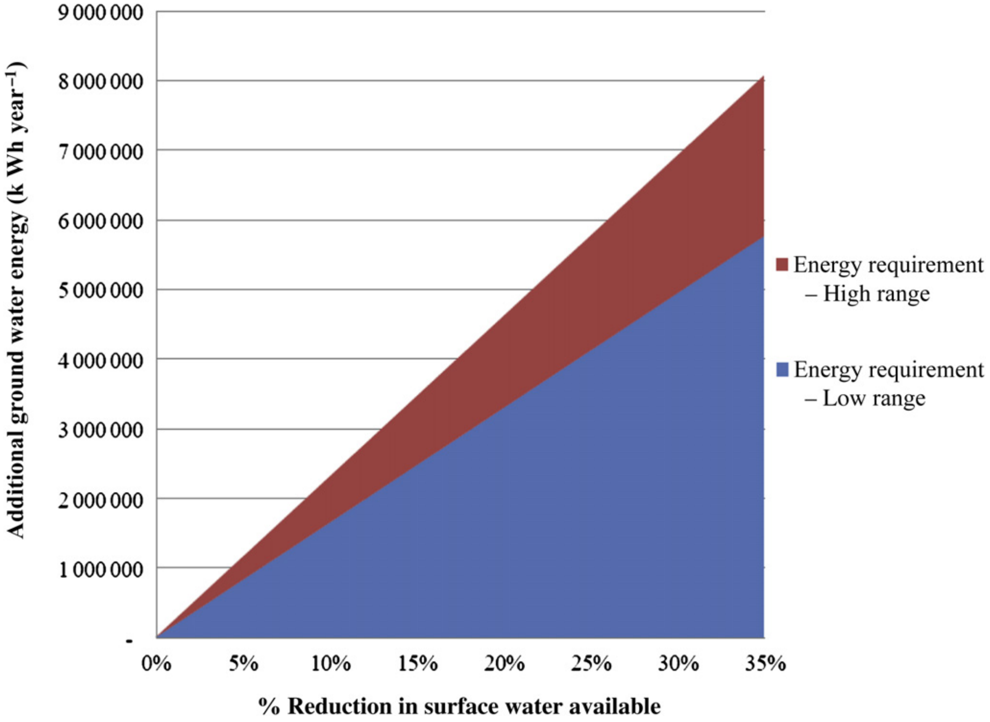

Figure 3 Additional energy requirement for JVWCD, the wholesale district, with decreasing surface water availability.

water withdrawals made from deeper aquifers in the Salt Lake Valley, which requires additional pumping to provide pressure to the system. Because of this, their energy requirement for water withdrawals and pressurization is significantly higher than a simpler surface water source and gravity-fed network. Savings for more energy-intensive water systems are also greater than a gravity-fed system if the agency is able to assist its customers in adopting a water conservation ethic. For example, using a case study site in Melbourne, Australia, Flower et al. (2007) found that, with a combination of structural and nonstructural demand management strategies, individual household water consumption could be reduced by 65% and indirect GHG emissions could be reduced by 63%. An interesting corollary is that the CEC also suggested that it may be possible to meet 95% of their energy efficiency goals indirectly through less-expensive water efficiency programs, emphasizing the gains to be made in the end-use sector for that region (CEC 2005; Alliance for Water Efficiency 2008).

Both initial water treatment and wastewater treatment are also large energy users within the water supply and consumption cycle and the energy requirement varies with the water quality of influent and the technology employed at the facility. Increased turbidity in incoming flow is likely to require additional treatment processes and infrastructure. More advanced water treatment methods such as ozonation, ultraviolet light disinfection, or additional nutrient removal are more energy intensive as well (EPRI 2002). Removal of higher concentrations of endocrine disrupting compounds requires very energy-intensive processes such as reverse osmosis treatment (Benotti et al. 2009). On the wastewater end, changes in the hydrologic cycle may also disrupt processes by concentrating effluent before it arrives at the plant, flooding facilities that discharge in coastal waters, or increasing water temperatures to a degree that they damage sewer and stormwater infrastructure or the biological processes that effectively remove contaminants. Reduced in-stream flows may also concentrate pollutants at a facility's outfall, eventually resulting in increasing water quality treatment standards within the plant to maintain the health of the public and ecosystems downstream. More stringent water quality regulation requires more extensive (and energy-intensive) infrastructure and processes.

Mitigation specific to the energy requirements of urban water systems under climate variability and change scenarios requires adaptive planning from the macroscopic view down to the individual water component. State agencies and district managers that are most familiar with the region or local area should incorporate energy costs (both actual and financial) and their resulting 'carbon footprint' into their extended-horizon cost/benefit analyses concerning resource development and capital improvements. Entities concerned with planning and administration of both water and energy may coordinate their efforts to make decisions that optimize the use of both resources. Water planning decisions that include and attempt to minimize energy expenditure improve the resiliency of the water system and provide an additional buffer against fluctuating energy pricing. Incorporating renewable energy sources (such as on-site solar, wind, or geothermal power) into urban water systems also improves resiliency when there are fluctuations in energy supply, allowing for critical water provision or treatment during natural hazards or events that interfere with power infrastructure. Diversifying water supply portfolios to include less traditional water sources like recycled water also minimizes energy costs where redistribution is not extensive. Colocation of water treatment and energy production facilities has been found to conserve a significant amount of energy by utilizing the same infrastructure components (intakes and outfalls) and by passing water used in the cooling processes of the power facility directly on site for treatment. Including biogas or cogeneration capacity at wastewater treatment plants also provides a substantial amount of energy that can increase resiliency at the plant and even serve as a potential energy offset (Show and Lee 2008). Finally, water education and conservation programs, including incentives for water- and energy-saving household appliances and fixtures, can be one of the most effective mitigation and adaptation tools available to water policy-makers.

Incorporating energy requirement on a water agency or district scale could include a multitude of the same strategies presented above but on a smaller scale. Such entities can foster adoption of a long-term water conservation ethic by participating in water education programs; offering incentives for water-conserving appliances, fixtures, and xeric landscapes; and implementing a staggered pricing structure for water use that encourages conservation and makes exorbitant water use more expensive. Other more infrastructure-centric strategies may also serve as a means to improve urban water system efficiency. Components of a water distribution or treatment system can often increase their energy efficiency by optimizing pump and groundwater operation (Bunn and Reynolds 2009) or by using a Supervisory Control and Data Acquisition (SCADA) system, as suggested by EPRI (1998, 1999), or characterization of water networks into hydraulic modeling software (Ramos and Ramos 2009). Likewise, implementation of a maintenance, inspection, and asset management program can point out problem areas of the system where additional energy savings may be realized and allow for interyear comparisons of component performance and operation. Finally, the incorporation of new technologies as they become available may also prove beneficial. An example might include investigating the potential for energy cost offsets with the selective removal of pressure reduction valves in favor of small hydropower energy generation or microturbines (Ramos and Mello 2007; Smith 2008). Whatever the method employed, meeting water demand in the future will require decision makers and agency managers to make smart choices that incorporate and address energy requirements and consider the two resources in tandem.

Most of an urban water system's vulnerability to climate variability concerning water and energy nexus topics can be described as a function of how much energy is necessary to maintain water services and how much energy will be needed in the future given climate and population growth drivers. How much water is necessary for energy and electricity generation is of less importance to the manager or director of a water district or agency than whether there is adequate energy to run the facilities. However, current trends in energy use, and projections to meet that use in the future, have ramifications for urban water systems. Several researchers have noted that the municipal per capita water use in the United States has leveled off in recent decades (Diamond and Moezzi 2004). The water withdrawals necessary for energy production have not, and are projected to increase in tandem with energy needs (Sovacool and Sovacool 2009). Water planners may need to take this new demand sector into account when looking for water supply sources to meet future demands. An example would be a city that is expecting transfers from agricultural uses to municipal systems to supply an expanded population. If a new generation plant is built nearby that is water intensive, the agricultural water may or may not be available to the city when the time comes to transfer. Climate variability, especially the prospect of reduced streamflows, would increase the competition between urban water systems and other sectors for any available supply.

5.06.4 Conclusion

This chapter reviewed climate vulnerabilities and adaptation approaches of urban water infrastructure systems. Taking an integrated approach, water supply, stormwater, and wastewater systems were considered together. Although the response of systems to climate variability is highly site and system specific, the chapter highlighted general vulnerabilities and adaptation strategies. A broader vulnerability concept requires the determination of the major threats to these resources from climate considerations and from other social and environmental issues. After these threats are identified for each resource, then the relative risk from natural and human-caused climate change can be compared with other environmental and social risks in order to adopt the optimal mitigation/adaptation strategy. Future climate has the real possibility resulting in increased energy use (Elcock 2010), coastal flooding and SLR (Purvis et al. 2008), river flooding, transportation problems, water supply problems (Gleick and Chalecki 1999), a decrease in public health, decreased water quality, increased bridge scour, and many other challenges to urban water infrastructure. An important part of the assessment of the challenges and developing solutions is to identify synergistic effects among the often independently operated subsystems of water supply, stormwater, and wastewater. Moreover, solutions to adaptation should be broader than presented in this chapter to be a part of a coherent regional strategy to ensure sustainable water resources.

An important limit to the analysis presented in this chapter is the narrow scope of the system considered. The system boundary considered is the urban water infrastructure system, which is linked to many other subsystems in cities as well as systems that are connected to urban areas, including agriculture, regional energy generation, regional water, and so on (Kirshen et al. 2008b), many of which are highlighted in this volume. Future systems analysis work will need to continue to expand to include the detailed considerations presented here along with those of the broader connectivities.

One other limitation is the focus on climate vulnerabilities. Urban water infrastructure systems are exposed to an array of pressures leading to vulnerabilities, including population growth, land use change, policy, and aging infrastructure. Future work must consider the relative importance of climate variability compared to the other pressures on the systems, which of course changes case by case. It is also expected that climate vulnerabilities of urban water infrastructure systems will be heightened when combined with pressures from urbanization, social change, and so on. This is especially likely for systems that are already stressed by existing conditions.

Typically, changes to urban water management that address vulnerabilities in general and climate vulnerabilities in particular approach urban water management in an integrated manner. The systemic nature of an urban watershed, especially when the drainage system works jointly with flooded urban landscape elements, makes it possible that some design solutions act in an ineffective way; however, it is also possible to attain better results via strategies applied in coordination with one another. Broadening this thought is the concept of IRP that takes a long-term portfolio approach where diversifying and integrating flexibility into the system leads to resilience. A key part of IRP is stakeholder involvement. The use of these broad approaches also requires the use of multicriteria decision-making approaches to evaluate urban watershed management alternatives based on achieving multiple objectives (Chung et al. 2011).

Besides new urban watershed management approaches, there are emerging technologies, policies, and interconnected factors that will serve to help systems adapt to climate variability and longer-term change and other vulnerabilities. Challenges with new approaches are typically related to policy, designer/planner experience, and cost. Local government design criteria for buildings and other infrastructure are, in general, not changing in response to the observed variability and longer-term changes in climate. Flood control and drainage design, for example, are based on frequency analysis of historical rainfall and streamflow data, which may not reflect recent or future climate. The recent economic downturn has helped to inhibit changes to policy that would require greater expenditures to provide the increased levels of protection; therefore, solutions from policy and funding perspectives are, in some cases, more important than technical guidance. For instance, Philadelphia's (Pennsylvania) Green City, Clean Waters is a 25-year plan that aims to protect and improve the watershed's stormwater problems resulting from its CSS, via LID application (Philadelphia Water Department 2011). In 2007, the State of Maryland passed the Stormwater Management Act, requiring all new developments to implement environmental site design to the maximum extent practicable, which highlights sustainable and better site design techniques (Boicourt et al. 2011). In San Jose, California, the Green Vision is a 15-year plan that provides the city with a road map to attain sustainability, via balancing of economic, environmental, and social community aspects (City of San Jose 2010). Other cities, such as Chicago, provide the population with several examples and additional resources available online to improve water resources sustainability (City of Chicago 2010).

Several strategies aiding the move toward more sustainable and resilient urban water infrastructure systems were noted. Implementing GI to manage stormwater provides a low-cost, ecologically focused approach to provide capacity to reduce stormwater runoff quantity and improve quality addressing challenges introduced by climate vulnerabilities. Decentralization of the water supply through rainwater harvesting provides redundancy but is also vulnerable to climate variability. Decentralized sanitation approaches and gray-water reuse present excellent opportunities to reduce the demand for potable water by helping to address the climate vulnerability of existing centralized water supply infrastructure systems. Last, the importance of considering the water–energy nexus was highlighted as an opportunity for reduction of resource consumption and harvesting of energy potential. The emerging approaches to urban watershed management display vulnerabilities to climate variability and change pressures; however, the improved resiliency they provide when applied in conjunction with centralized elements may be superior to centralized systems alone. More research is needed in general and on case-by-case basis.

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5.07 Impacts of Urbanization on Precipitation and Storms: Physical Insights and Vulnerabilities

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5.07.1 Introduction

On January 19, 2011, an unusual weather event occurred. The National Weather Service Web site (http://www.crh.noaa.gov/news/display_cmsstory.php?wfo=ddc&storyid=62980&source=0) described the event in the following way: "the atmosphere was cold and moist with low clouds and fog preceding the formation of the snow. It appears that two slaughter plants and a power generating plant (upwind of the region) contributed to the snow as ice nuclei and copious amounts of water vapor were fed into the boundary layer. East/southeast winds carried the vapor and nuclei aloft into the lower clouds and then precipitated out as snow downwind (**Figure 1**) of the source. Snowfall of as much as 0.7″ was reported in the snowfield with no snow observed at all outside of this area." The snowfall plume is apparent in Doppler radar images (**Figure 2(a)**) and satellite depictions of snow cover (**Figure 2(b)**).

Though unusual, this example illustrates how human activity in an urban environment affected a precipitation event. The scholarly literature continues to indicate that urbanization, deforestation, irrigated landscapes, impounded structures, and pollution can alter the frequency, intensity, or occurrence of precipitation (Mahmood et al. 2010). In fact, the Intergovernmental Panel on Climate Change (IPCC) (Trenberth et al. 2007) specifically mentioned an emerging interest in how urban environments—the focus of this discussion—modify hydrometeorological and climate system. While the climate discourse has been primarily centered around greenhouse gas emissions, urban climate effects are conclusively documented.

Seto and Shepherd (2009) stated that "the built environment characterized by urbanization is a significant forcing function on the weather-climate system because it is a heat source, a poor storage system for water, an impediment to atmospheric motion, and a source of aerosols (e.g., pollutants)." **Table 1** (adapted from Seto and Shepherd 2009) presents multiple ways that urbanization can impact hydrometeorological and climate processes.

The most common manifestation of urban climate is the urban heat island (UHI). The UHI is typically characterized by warmer skin, surface, and canopy temperatures in urban landscapes due to heat-retaining materials (e.g., asphalt, concrete), lack of vegetation, and excessive anthropogenic heat sources. Surface geometry (e.g., as expressed by sky view factor) is also an important element of the UHI; surface geometry also increases the surface area for solar absorption, leads to multiple reflections and decreased albedo, and affects turbulent transport (sheltering effects). All of which impact the UHI. Grimmond et al. (2010) and Yow (2007) are excellent resources for information on the energetics, thermal properties, and dynamics associated with UHIs.

UHIs are somewhat common in both scientific and public vernacular. It is a conclusive example of human alteration to the Earth's climate system. However, the literature has also revealed that urban landscapes and associated pollution may also alter components of the water cycle, particularly clouds, precipitation, and land surface hydrology (Bentley et al. 2010; Niyogi et al. 2011; Grimmond et al. 2010; Hidalgo et al. 2008; Mills 2007; Shepherd et al. 2010a, 2011). The motivation herein is to review the theoretical and physical basis for how urbanization influences the spatiotemporal nature of precipitation and convective activity. This is particularly important for the following reasons:

1. For the first time in history, the majority of the world's population lives in urban environments (Hand and Shepherd 2009) and this number will increase to over 80%

http://dx.doi.org/10.1016/B978-0-12-384703-4.00503-7

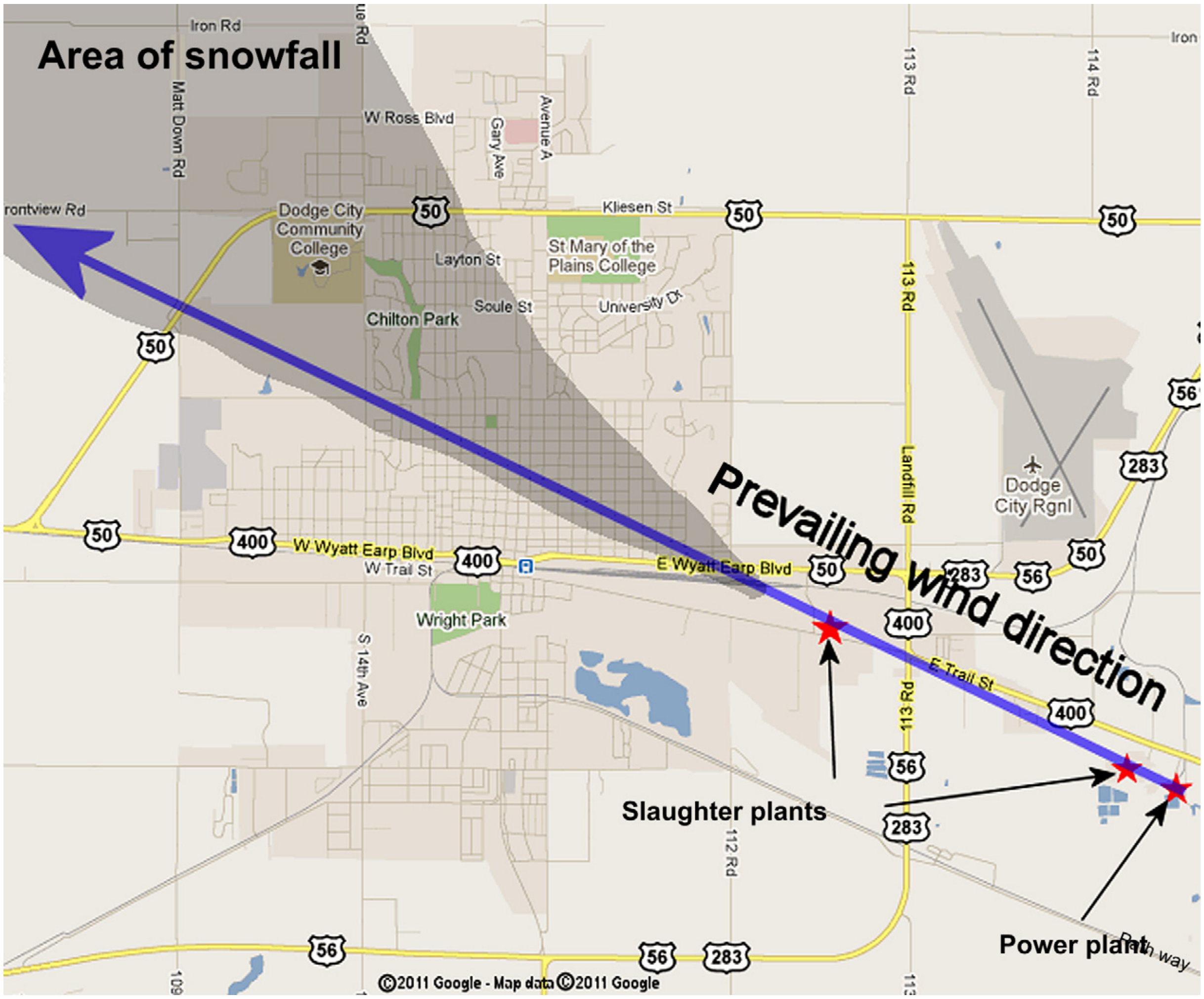
Area of snowfall
Prevailing wind direction
Slaughter plants
Power plant
Iron Rd
W Ross Blvd
Matt Down Rd
Gary Ave
Avenue A
Kliesen St
Dodge City Community College
St Mary of the Plains College
Layton St
Chilton Park
Soule St
University Dr
113 Rd
114 Rd
Landfill Rd
Dodge City Rgnl
W Wyatt Earp Blvd
W Trail St
E Wyatt Earp Blvd
Wright Park
S 14th Ave
E Trail St
112 Rd
50
56
283
400
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Figure 1 Dodge city, Kansas area and downwind region of unusual snow event. Source: National Weather Service; Shepherd J. M. and T. L. Mote, 2011: Can cities create their own snowfall?: what observations are required to find out? Earthzine, Special Urban Monitoring Theme Issue. [Available online at http://www.earthzine.org/themes-page/urban-monitoring/.]

by 2030 (UNFPA 2007) (Figure 3). This means that urban land cover and air quality degradation will continue to expand and expose more people to vulnerabilities associated with urban climates.

2. Convective processes and precipitation are critical components in the global water cycle and a key proxy for climate, but they exhibit variability at a range of scales from local to global.
3. Urban–hydrometeorological–atmospheric interactions have major societal implications for weather forecasting, climate diagnostics and prediction, flood management, water resource management, urban planning design, and agriculture.

5.07.2 Vulnerabilities in the Coupled Human Natural System

It is clear that the urban rainfall effect (URE) is of scientific interest because there are clear linkages to contemporary research and forecast problems in meteorology, climatology, hydrology, and geography systems. However, precipitation in an urban setting is strongly coupled to key societal processes and decision trees. An array of vulnerabilities may be linked to urban precipitation climatologies and variability:

1. Urban flooding: Jurisdictions are increasingly interested in the complex interplay of the urban environment and the atmospheric and land surface components of the water cycle. Shepherd et al. (2011) raised important questions about whether storm water management, drainage systems (Burian et al. 2004), and urban planning consider the shifting precipitation regimes associated with large-scale climate and urban climate. For example, hydroclimate experts have warned that current urban flood assessment and storm water management are based on hydroclimate stationarity assumptions and outdated assumptions concerning rainfall intensity and frequency. Intensity, duration, and frequency resources and methodologies must be modified to reflect nonstationarity and new understanding of local-to-regional hydrometeorological forcing.

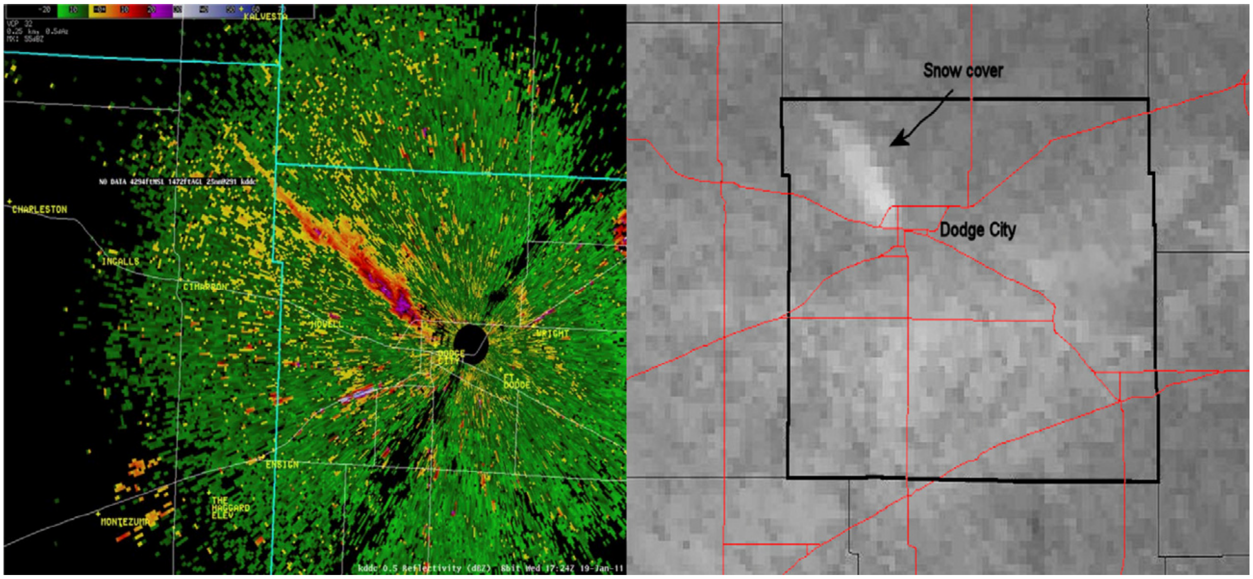

Figure 2 Dodge city snow event as captured by a (a) radar image at 1124 LST and (b) satellite image after the event. Source: National Weather Service; Shepherd J. M. and T. L. Mote, 2011: Can cities create their own snowfall?: what observations are required to find out? Earthzine, Special Urban Monitoring Theme Issue. Available online at http://www.earthzine.org/themes-page/urban-monitoring/.

Table 1 Alterations of surface and atmospheric processes by changes in urban land cover, urban aerosol loading in the atmosphere, and anthropogenic greenhouse gas emissions

Weather or climate processes	*Urban land cover*	*Urban aerosols*	*Anthropogenic greenhouse gas emissions*
UHI and mean surface temperature record	Surface energy budget	Insolation, direct aerosol effect	Radiative warming and feedback
Wind flow and turbulence	Surface energy budget, urban morphological parameters, mechanical turbulence, bifurcated flow	Direct and indirect aerosol effects and related dynamic/thermodynamic response, dispersion, and transport	Radiative warming and feedback
Clouds and precipitation	Surface energy budget, UHI destabilization, UHI meso-circulations, UHI-induced convergence zones	Aerosol indirect effects on cloud–precipitation microphysics, insolation effects	Radiative warming and feedback
Land surface hydrology	Surface runoff, reduced infiltration, less evapotranspiration	Aerosol indirect effects on cloud–microphysical and precipitation processes	Radiative warming and feedback
Carbon cycle	Replacement of high net primary productivity land with impervious surface	Black carbon aerosols	Radiative warming and feedback, fluxes of carbon dioxide
Nitrogen cycle	Combustion, fertilization, sewage release, runoff	Acid rain, nitrates	Radiative warming and feedback, NO_x emissions

Adapted from Seto, K., and J. M. Shepherd, 2009: Global urban land-use trends and climate impacts. *Curr. Opin. Environ. Sustain.*, doi:10.1016/j.cosust.2009.07.012.

2. Urban planning: It is reasonable to consider how contemporary and future cities are planned. Stone et al. (2010) and Shepherd et al. (2010b) have shown that urban land cover is a significant driver of climate at the urban and associated regional scales. Such research is intriguing and raises questions about urban governance and the inclusion of urban hydroclimate science in policy and decision making. It is not unreasonable to consider the planning of an urban landscape with an eye toward mitigating or maximizing precipitation for a region's agriculture or water supply needs.
3. Public health: Urban precipitation climatology may be associated with an array of health issues, ranging from West Nile virus to asthma. Socioeconomics and public health practices are first-order factors, but it is plausible that areas which may experience more rainfall in an urban regime could be more susceptible to water-borne diseases (e.g., dysentery or cholera) or vector-borne diseases (e.g., malaria, dengue, and West Nile virus). Further, thunderstorms were associated with more hospital admissions for respiratory distress and asthma for metropolitan Atlanta, Georgia (Grundstein et al. 2008).
4. Water resource management: In the face of increasing drought and the need for additional surface water supply, Shepherd and Mote (2009) have argued that future water supply reservoirs might be placed in urban rainfall anomaly regions to optimize recharge, particularly in the warm season. For example, Mote et al. (2007) noted that eastern

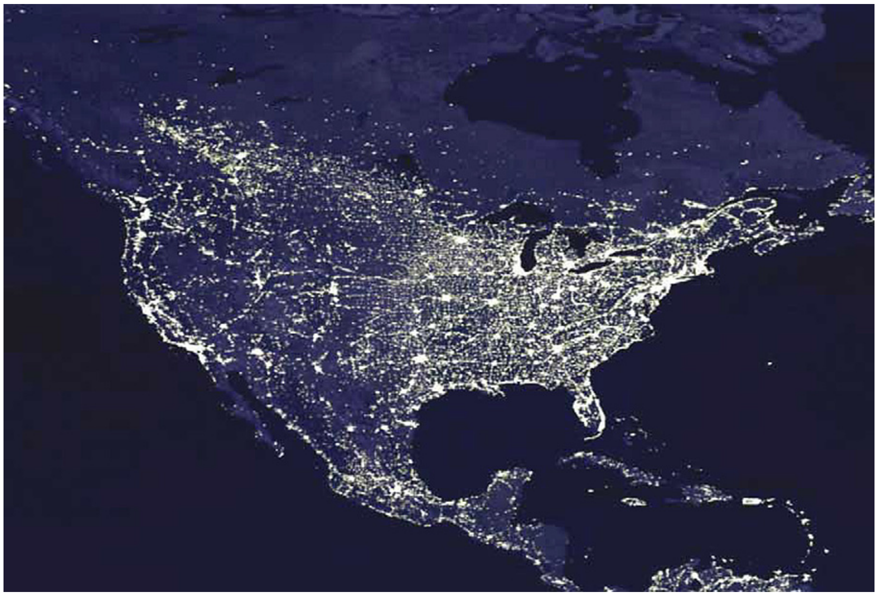

Figure 3 Defense Meteorological Satellite Program (DMSP)/Optical Line Scanner (OLS) data showing lights at night in the United States. Source: NASA (http://www.nasa.gov/vision/earth/lookingatearth/NIGHTLIGHTS.html). The lights, to a first order, are a proxy for urbanization.

suburbs of Atlanta (within 50–100 km) receive more warm season rainfall (more on this in later sections), yet Figure 4 shows that this region has no new reservoirs planned.

5. Strategic systems management: The placement of new agricultural lands, sensitive electrical infrastructure, flood management, or industrial facilities might be informed by knowledge of urban lightning or precipitation anomalies.

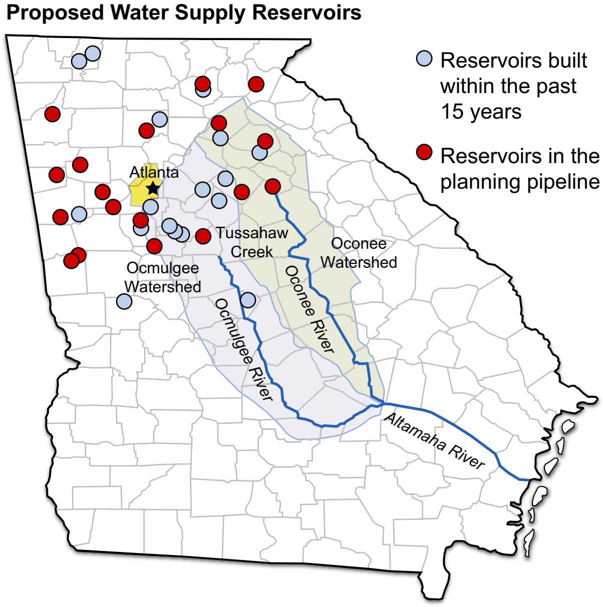
Proposed Water Supply Reservoirs
○ Reservoirs built within the past 15 years
● Reservoirs in the planning pipeline
Atlanta
Tussahaw Creek
Oconee Watershed
Ocmulgee Watershed
Ocmulgee River
Oconee River
Altamaha River

Figure 4 Proposed water supply reservoirs (courtesy of the Army Corps of Engineers). Red dots are planned reservoirs. *Source: Shepherd, J. M., and T. L. Mote, 2009: Urban effects on rainfall variability: potential implications for Georgia's water supply. Proceedings of the 2009 Georgia Water Resources Conference, 6 pp.*

Clearly, urban weather and climate are integrated in the economics of urban regions. Such costs might include flood damages, airport closures, health-insurance costs, or regional transportation infrastructure. Snowstorms in 2010 and 2011 crippled Washington, DC (i.e., 'Snowmaggedon') and revealed cascading scales of vulnerability ranging from the poorest citizen of the District of Columbia to the President of the United States.

A rare tornado in the central business district of Atlanta, Georgia, in 2008 and the crippling tornado outbreak in Joplin, Missouri, in 2011 reveal potential infrastructure vulnerabilities and the need to consider severe weather in urban building codes. Thomas (2011) recently discussed the vulnerabilities of hospitals to severe weather in light of the Joplin event. She notes that "… extreme weather can cause building failures that ultimately lead to interruptions in the continuity of care. The impacts are not momentary. From post traumatic stress disorder to the costs of structural rebuilding, the affects can be long-lasting. Yet, structural mitigation, while not a full panacea, can offer some protection to keep buildings and people safe. The World Health Organization (WHO) calculates that the price for retrofitting the non-structural items (e.g., moveable carts, trays) costs as little as 1% of the value of a hospital, while possibly protecting up to 90% of the hospital's assets. According to FEMA, the most common points of hospital failure from storms are the elevator crankcases, windows and generators. Bolstering protection of these building assets costs magnitudes less than the cost to rebuild." While specific to hospital infrastructure, such recommendations are relevant to any urban building infrastructure facing the threat of increased storm activity or flooding.

While urban changes to the hydroclimate have been discussed herein, one must not overlook the coupled influenced and heightened vulnerability due to the background climate gases (Seto and Shepherd 2009). Reports, composed of international expertise, continue to call for renewed resources and research to address urban hydroclimate interactions (Dabberdt et al. 2000; NOAA OFCM 2004; NRC 2012).

5.07.2.1 Controversy Over the Sign of Change

Though methods and data availability continue to improve, there is still uncertainty and scientific debate about whether urban environments increase rainfall, decrease rainfall, or have no effect on rainfall. The consensus in the literature suggests that some type of enhancement is the dominant sign change; however, other results are compelling (see Section 5.07.2). However, it is worth noting that there is some literature that finds conflicting results, albeit a relative minority of studies. Hughes (2006) found no statistical evidence supporting UREs in cities of the United Kingdom, although she did not rule them out either. Matheson and Ashie (2008) found in modeling simulations for Tokyo that rainfall was increased or decreased due to the inclusion of the city, as a function of the prevailing wind. However, their results do suggest that urban landscape can modify precipitating systems. Trusilova et al. (2008) coupled atmosphere–land surface (CALS) model simulations of European climate sensitivity to urban land cover offered mixed results. Shepherd et al. (2010a) summarized their results by noting that they found "statistically significant increases (decreases) in winter (summer) precipitation in their urban simulations as compared to the pre-urban simulations." This study was interesting but used fairly coarse model resolution (10 km) and cumulus (not explicit microphysics) parameterization for cloud–precipitation processes.

Kaufmann et al. (2007), using statistical and econometric models, found evidence of reduced precipitation after urban development throughout the Pearl River Delta of China. They suggested that reductions in surface hydrology could explain the changes. Guo et al. (2006) used a similar argument to explain decreased cumulative rainfall around Beijing. Zhang et al. (2009) showed that urban land cover in Beijing reduced ground evaporation and evapotranspiration, which was important for rainfall formation. One important factor that was missing in the studies describing precipitation suppression in Asia is aerosols or pollution.

Aerosols (e.g., pollutants) have been shown to suppress precipitation. This inverse relationship between aerosol load and precipitation has been summarized in Lin et al. (2011), Stjern et al. (2011), and Rosenfeld et al. (2008). Asia is a heavily polluted region and a thorough climatological assessment of precipitation change in the region must consider the recent trends in the spatiotemporal aerosol distribution. Recent studies (Rosenfeld et al. 2008; van den Heever and Cotton 2007) have explored the role of giant cloud condensation nuclei (CCN) (enhancement) and smaller CCN (suppression). However, the synergistic role of urban aerosols and land cover on precipitation is still not conclusive and requires additional study. It is likely that topography, meteorology, aerosol type, and continentality determine the order of influence of aerosols. For example, Jin and Shepherd (2008) argued that aerosol effects are more dominant on maritime cloud droplet formation. Stjern et al. (2011) found no statistical evidence that aerosols have affected drizzle or light rain climatologies in Europe. Lin et al. (2011) firmly established the inverse relationship between aerosols and precipitation.

5.07.3 Historical Evidence of the 'URE'

While contemporary methods and studies have advance knowledge of the URE, it is useful to consider the historical legacy of this field. Horton (1921) observed that thunderstorms seemed to develop over large cities. Kratzer (1937, 1956) further advanced the notion of urban alteration of precipitation. However, the pioneering text 'The Climate of Towns' by Helmut Landsberg (1956) elevated the possibility that large urban areas affect rainfall. Over the next several decades, more research emerged on the topic. Several studies were focused on a hypothesis that industrial, urban regions southeast of Chicago, Illinois, such as La Porte, Indiana, had enhanced cumulative precipitation due to urban or aerosol effects. Stout (1962) and Changnon (1968) led early investigations related to the 'La Porte Anomaly' although they were inconclusive (Lowry 1998). More importantly, these early studies stimulated the first golden age in research on the topic.

The prevailing hypothesis in early studies, many advanced by European scholars, was that rainfall was enhanced primarily over or downwind of urban areas (Landsberg, 1970; Huff and Changnon, 1972a,b). A major North American field program, the METROpolitan Meteorological EXperiment (METROMEX), was a large-scale effort to test such hypotheses and advance scientific understanding of urban precipitation climatologies and physical mechanisms. A key legacy of METROMEX is that it provided some of the earliest and most rigorous hypotheses about physical forcing of urban hydroclimate interactions. METROMEX employed many observational strategies including special rain gauge networks, balloon soundings, and weather radar. Shepherd et al. (2010a) summarized key findings from the series of scholarly publications from this multicity investigation:

1. Enhanced cumulative precipitation (see **Figure 5** as an example) by urban effects are typically 25–75 km downwind of a city during warm season months (Changnon et al. 1977; Huff and Vogel 1978; Changnon 1979; Braham 1981),
2. Cumulative amounts were enhanced between 5 and 25% over background values (Changnon et al. 1981, 1991), and
3. The size of an urban area influenced the horizontal extent and magnitude of urban enhanced precipitation (Changnon 1992).

Lowry (1998) raised questions about the methodologies and research framework applied during METROMEX and post-METROMEX studies. He further hinted that such deficiencies could 'create' the anomaly regions. His recommendations, summarized below, would provide key guidance to contemporary studies on urban rainfall. Lowry (1998) recommended:

1. "Designed experiments—especially legitimate controls and, where appropriate, stratification schemes—in which explicitly stated hypotheses are tested by means of standard statistical methods.
2. Replication of the experiments in several urban areas.
3. Use of spatially small, and temporally short, experimental units reflecting the discontinuous nature of precipitating systems.
4. Disaggregation of standard climatic data to increase sample size and avoid merging effects between dissimilar synoptic weather systems."

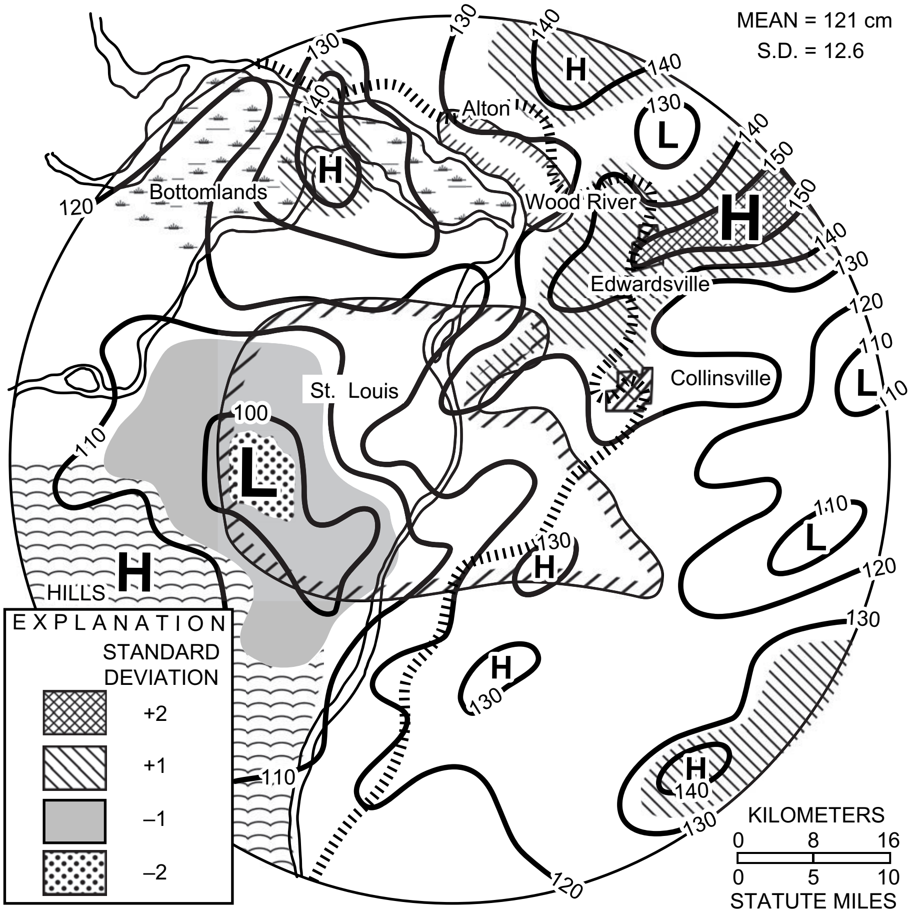

Figure 5 METROMEX, total summer rainfall (cm), 1971–75. Source: Changnon, S. A., F. A. Huff, P. T. Schickedanz, and J. L. Vogel. 1977. Weather anomalies and impacts: In summary of METROMEX Vol. I. Illinois State Water Survey Bulletin 62, 260 pp.

As noted earlier, the literature has found conflicting results to METROMEX Tayanc and Toros (1997) found no evidence that four large Turkish cities had modified climatological rainfall patterns. Robaa (2003) argued that an inverse relationship may exist between urbanization and cumulative precipitation around Cairo, Egypt. In future sections, other recent findings that support or refute the METROMEX results are discussed. The text will also explore the physical mechanisms that link urbanization to precipitation changes. Aerosols – for example, their concentration, size, and to a lesser extent composition – have been shown to suppress or enhance precipitation and/or lightning (Rosenfeld et al. 2008). Regardless of the sign of the change, it is clear from the literature that urbanization alters the hydroclimate system in diverse ways.

5.07.4 Post-METROMEX Era Perspective

After METROMEX and the subsequent questions about the validity of its findings, momentum on the topic slowed. Balling and Brazel (1987) noted a greater frequency of occurrence of late afternoon thunderstorms around the Phoenix area. They attributed the increase in frequency to rapid urbanization in this otherwise arid region. Selover (1997) noted that moving summer convective storms were altered by Phoenix. Later work by Diem and Brown (2003) and Shepherd (2006) corroborated the notion of a URE in the Phoenix area, particularly in the Lower Verde region of Phoenix. Shepherd (2006) hypothesized that urban-induced mesocirculations might interact with outflow boundaries from the mountain-forced convection to explain the location of the Lower Verde anomaly.

Jauregui and Romales (1996) found significant correlations between the daytime UHI and the intensity of rain showers during the wet season (May–October) in Mexico City, Mexico. They also argued that the frequency of intense rain showers had increased as a result of urban growth. Changnon and Westcott (2002) found a similar tendency toward more heavy rainstorms in recent decades for a selection of urban locations.

Bornstein and LeRoy (1990) were one of the first research groups to study the URE in a 'megalopolis' city. Using weather radar, they found that maximum convective rainfall was found on the lateral edges and downwind of New York City. This study was important because it further demonstrated the value of weather radar to overcome limitations associated with the sporadic nature and point source availability of rain gauges. Precipitation, unlike temperature, is highly variable in space and time, which can be problematic for point source measurements. This study also solidified the notion that cities not only initiate or enhance convection but also modify the structure and progression of storms. Recently, Niyogi et al. (2011), using Doppler radar data, found that the city of Indianapolis, Indiana, modifies a significant number of storms approaching the urban environment. Such studies indicate that the urban effect is not only apparent in the initiation of convection in weak large-scale forcing environments as previously argued, but it can also modify preexisting convection. Shem and Shepherd (2009) found similar results in their modeling simulations of moving convective systems in Atlanta, Georgia.

Shepherd et al. (2002) introduced a new approach for examining the URE. They used satellite-based instrumentation designed to measure precipitation from space. Space-borne estimates enabled the investigation of multiple cities simultaneously as opposed to one or two urban locations. This approach overcomes one of the limitations of earlier work identified by Lowry (1998). On the other hand, the satellite-derived rainfall estimates had relative coarse spatial resolution and well-known measurement biases. Shepherd et al. (2002), using a short 3-year period, found evidence of precipitation anomalies in the climatological downwind region of several major cities in the southeastern United States. Diem et al. (2004) and Shepherd (2004) had a scholarly discourse on the merits of the findings, appropriate scale, and methodologies in Shepherd et al. (2002). Souch and Grimmond (2006) noted that this paper may have 'reinvigorated' the urban climate community on the question of UREs.

Shortly after Shepherd et al. (2002) had published, Dixon and Mote (2003) presented evidence that in the moist environment of Atlanta, Georgia, some nocturnal convective storms might have been initiated by the urban landscape itself. During the same period of time, a Japanese paper, Fujibe (2003), stated that increased convective activity downwind of large cities like Tokyo may be due to the enhanced surface convergence in the urban environment (more in the following sections). Shepherd and Burian (2003) extended the satellite-based methodology to a large coastal–urban complex, Houston, Texas, and found that rainfall anomalies in the data were spatially consistent with lightning flash density anomalies described by Orville et al. (2001). Orville et al. (2001), and later Steiger and Orville (2003), attributed the lightning anomalies to urban landscape or industrial–urban aerosols. Further details are provided in the following sections.

In 2005, Shepherd reviewed the current literature related to urban convection and rainfall effects. While the review was a timely contribution to the literature, he also provided a set of recommendations to move understanding and predictive capability forward on the topic: The recommendations of Shepherd (2005) were as follows:

1. "New observing systems must be developed to monitor and track anthropogenic and natural aerosols, land cover/land use changes, cloud microphysics, and precipitation processes,
2. Modeling systems that explicitly resolve aerosols, cloud microphysics, complex land surfaces, and precipitation evolution so that a more conclusive understanding of the feedback and interactions can be attained,
3. Implementation of urban parameterizations at the local scale to resolve urban canyon, dynamics, and flux processes, particularly in terms of roughness, surface cover properties, low-level moisture associated with irrigation, and aerosols,
4. Field studies to validate satellite observations and modeling simulations of urban-precipitation processes and to extend basic understanding of the processes involved,
5. Climate modeling systems that adequately characterize the urban environment are required to understand the aggregate roles of global urban surfaces on the Earth's climate system, particularly the precipitation component of the water cycle under different growth and climate scenarios,
6. Assessment of the impact of urban-induced rainfall on societal applications."

Burian and Shepherd (2005) confirmed the satellite-based results of Shepherd and Burian (2003) by using historical gauge data to show that "urban area and the downwind regions of Houston, Texas (USA) had 59 and 30% respectively greater cumulative rainfall between noon to midnight in the warm season compared to the upwind region." As noted earlier, two studies (Diem and Brown 2003; Shepherd 2006) identified spatial anomalies around the northeastern suburbs and exurbs of Phoenix during the monsoon season. Shepherd (2006) results suggested that the anomaly regions had 12–14% more cumulative precipitation in the posturban (1950–2003) period as compared to the preurban (1895–1949) period. Shepherd argued that outflow boundaries from mountain thunderstorms might be interacting with the urban circulation to explain the location of the anomaly. Simultaneously, Chen et al. (2007) posed a similar hypothesis to explain a nocturnal anomaly around Taipei (Taiwan).

One of the most compelling studies to date is Mote et al. (2007). They employed a radar analysis to look at warm season (2002–06) composites of precipitation climatology. Figure 5 (left panel) shows the greater rainfall totals expected in the Blue Ridge mountains of north Georgia and in the coastal plain to the south. More interestingly, there is an anomaly of higher rainfall amounts over and east of the Atlanta, Georgia, metropolitan area even though, climatologically, the entire area is similar. They found that this 'downwind area' receives up to 30% more warm season rainfall during the evening and early morning hours. It should be noted that this study stratified cased days to remove large-scale forcing, a key recommendation of Lowry (1998). This study is also compelling because it successfully establishes that the radar climatology strongly reveals the mesoscale and topographic signatures of rainfall in Georgia. Diem (2008) extended the epochal analysis of Diem and Mote (2005) to confirm, using long-term climatological analysis, that a rainfall anomaly exists in the northeast suburbs of Atlanta. Bentley et al. (2010) has extended the Mote et al. (2007) radar study and found that an array of downwind 'anomaly' regions may exist and, perhaps, some upwind anomalies as well. This is an important point to mention that, for a given day, upwind and downwind are a function of the prevailing wind such that a downwind anomaly for a given day may differ from the climatological downwind region, which is based on average flow conditions. In a compelling study, Ashley et al. (2012) conducted a climatological synthesis of urbanization effects on an array of cities in the southeastern US using a 10-year radar data analysis. They confirmed "positive urban amplification of thunderstorm frequency and intensity for major cities."

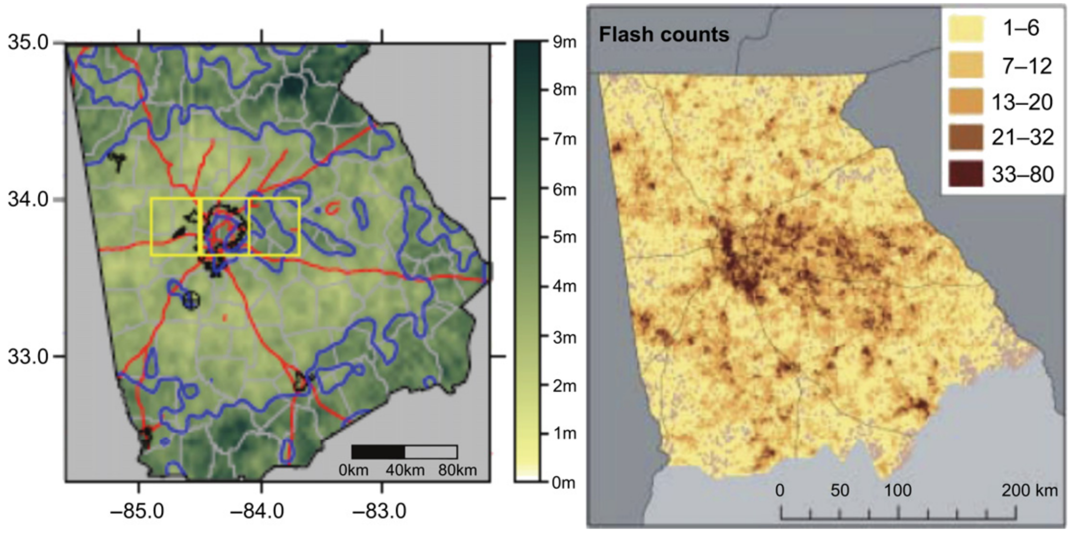

Figure 6 Average daily rainfall (shaded and units of millimeters) from Jun.–Aug. 2002 composited for days with weak atmospheric forcing. The 5-mm contour is shown in blue, and the yellow boxes represent the mean upwind (left), city (center), and downwind (right) regions (Left) and lightning flash anomalies (May–Sep. (1995–2003) on days dominated by weak atmospheric forcing) (right) in Atlanta, Georgia. See Mote et al. (2007) or Stallins and Rose (2008) for further information on methods and data.

5.07.5 Beyond Spatiotemporal Rainfall Climatology: Urban Effects and Other Related Hazards

5.07.5.1 Rainfall Intensity and Frequency

Since the URE is primarily associated with convection, it is logical that urban effects might be observable in other convective-related processes (e.g., heavy rainfall rates, lightning, and flooding). Rose et al. (2008) used cloud-to-ground (CG) lightning data and North American Regional Reanalysis (NARR) rainfall data set to reveal lightning enhancements in the same downwind anomaly region (Figure 6, right panel) identified by Mote et al. (2007). Stallins and Rose (2008) provided an excellent review of urban effects on lightning and highlight several global studies on the topic. The possible mechanism will be discussed later in the text.

Hand and Shepherd (2009) used a blended product called the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis and the Oklahoma mesoscale observational network to confirm not only a statistically significant rainfall anomaly in the north–northeast suburbs of Oklahoma City but also a tendency for heavier rainfall events to occur in the same region. This study was novel because it was the first application of a merged satellite product incorporating infrared, passive microwave, and rain gauge data rather than only satellite precipitation radar data. Consistent with Rose et al. (2008), Hand and Shepherd (2009) noted a fairly strong relation between prevailing wind and downwind anomaly regions. More importantly, Hand and Shepherd (2009) also established that such satellite-based estimates are relatively accurate when validated against ground-based rain gauge networks (at the appropriate scale) and can be useful in investigating rapidly developing urban regions around the globe. Basara et al. (2009) discussed a new fine-scale Oklahoma City micronet with observations in the central business district. Such measurements are rare and will enhance our research capacity going forward.

Kishtawal et al. (2009) used historical gauge networks and the TRMM precipitation radar to show that heavy rainfall events increased in urbanized regions of India compared to rural stations (Figure 7). Mitra et al. (2011) also used gauge data and satellite rainfall estimates to study the oft-neglected pre-monsoonal rainfall climatology of India. They found that urban stations in the region of Kolkata, India, have positive trends in pre-monsoonal rainfall. A forthcoming modeling effort by Mitra and Shepherd (personal communication) further confirms that 'Nor'westor' convective systems may interact with the urban landscape to affect the evolution of rainfall in the region.

Halfon et al. (2009) noted increased cumulative precipitation amounts downwind of Tel Aviv, Israel. Chang et al. (2009) noted the role that urban land cover played, through boundary later and flux alterations, on a heavy rainfall event in Mumbai, India. Meng et al. (2007) also used ground radar-based analysis in an innovative study which presented evidence that the urban land cover associated with Guangzhou City (China) intensified thunderstorms associated with a tropical cyclone. Radar echoes were maximized over the urban area as also noted by Shem and Shepherd (2009) and Niyogi et al. (2011). Inamura et al. (2011) used ensemble simulations with a large number of members to investigate the effects of Tokyo's landscape on heavy rainfall. They found that the urban effects of Tokyo modified the wind convergence and rainfall leeward of the urban area. Li et al. (2011) associated rapid urbanization in the Pearl River Delta region of China with an increase in strong precipitation and convective events. Miao et al. (2011) used a mesoscale model with high fidelity representation of urban canopy. Their results confirmed that Beijing can modify storms by splitting them or enhancing the amount of rainfall. They attributed the modification to thermal (sensible and latent heat) transport rather than momentum transport (more on mechanisms later). Zhang et al. (2010) noted in the Yangtze River Delta Economic Belt that urban areas experience 15%

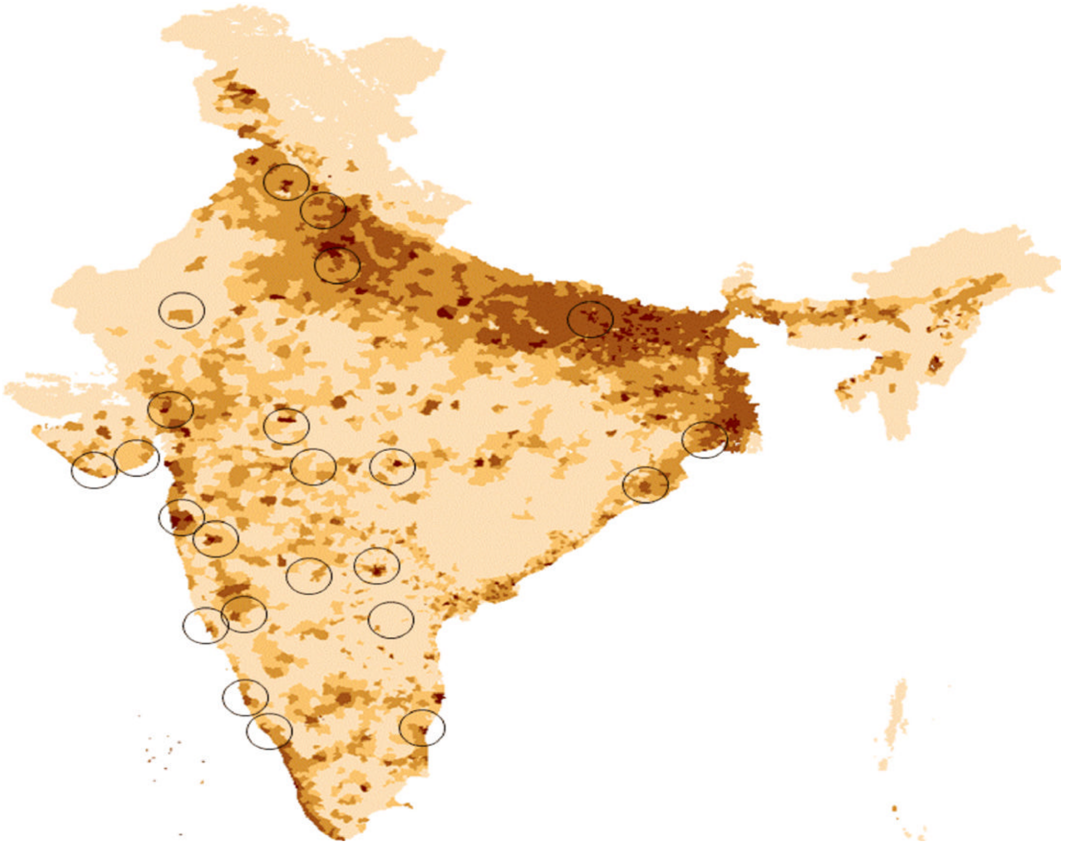

Figure 7 Circles represent the location of stations where the frequency of heavy precipitation events exhibits a positive trend with 99% confidence. The change in population density between 1990 and 2000 is shown in the background (from Kishtawal et al. 2009). Darker colors represent larger changes in population density. The darkest colors are indicators of cities.

more rainfall over the city and leeward, but that the effect was most prevalent during the summer.

5.07.5.2 Flooding

In 2010 and 2011, a number of cities worldwide experienced severe urban flooding. Ntelekos et al. (2007) showed that both the urban landscape and pollution may have assisted in priming the atmosphere for convection that led to flooding in the Baltimore—Washington area. Shepherd et al. (2011) argued that the urban landscape may have enhanced precipitation associated with a large-scale flooding event in Atlanta, Georgia. Though synoptic and mesoscale processes described the 'big picture' flooding event, localized regions of enhancements in the downwind part of the city may have been urban forced (Figure 8). They also confirmed that the urban landscape accelerated the land surface hydrological response. Shepherd et al. (2011) stated that "previous studies have noted the role that the urban environment has on the hydrologic cycle, including runoff, infiltration, evapotranspiration, and precipitation (see Reynolds et al. 2008, for a review). Reynolds et al. (2008) found that impervious surfaces in Houston distributed stormwater to conveyance systems with more volume over a shorter amount of time, which increases the risk of overwhelming the capacity of the system." It is suggested that in considering urban effects on the urban hydrological cycle, one must consider precipitation–urban interactions as carefully as they consider the evapotranspiration–urban or runoff–urban relationships, which tend to be more understood.

5.07.5.3 Lightning

Heavy convective activity and rainfall events are typically associated with lightning. Thus, it is not surprising that researchers have also identified a potential 'urban lightning effect,' The advent of ground-based and space-based lightning detection systems has advanced our ability to investigate this facet of the problem. Two overarching findings have emerged (Stallins and Rose 2008). They are summarized in Shepherd et al. (2010a): "(1) cloud-to-ground negative polarity flash densities increase, particularly downwind of the city center and (2) the percentage of positive polarity cloud-to-ground flashes decrease in the vicinity of cities." The reader should consult Stallins and Rose (2008) for a summary of the range of geographic and climatological regimes that have experienced an urban CG lightning effect.

Studies have mainly noted higher negative CG flash densities and decreased positive flash production within 100 km of the urban center (Stallins and Rose 2008). Because lightning is inherently associated with convection, it is not surprising that lightning and rainfall anomalies around cities would be consistent. This is clearly evident in Figure 5, for example,

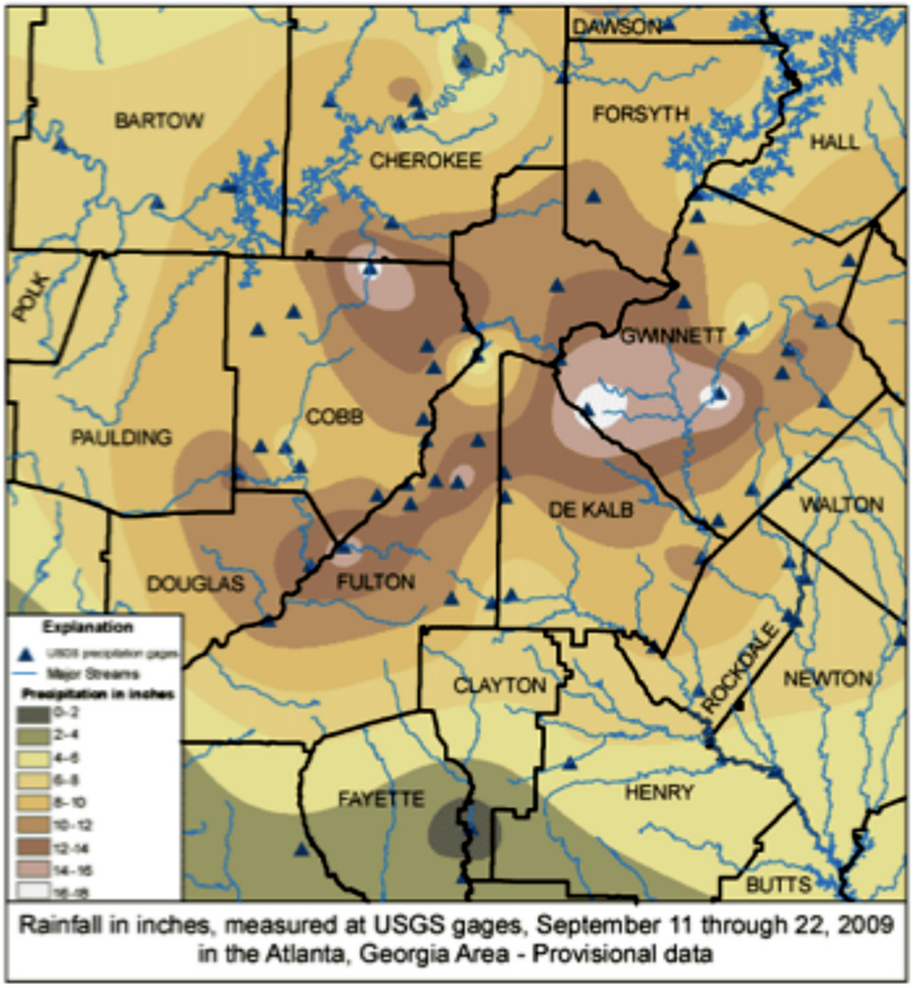
DAWSON
BARTOW
CHEROKEE
FORSYTH
HALL
POLK
GWINNETT
COBB
PAULDING
WALTON
DE KALB
DOUGLAS
FULTON
ROCKDALE
NEWTON
CLAYTON
FAYETTE
HENRY
BUTTS
Explanation
USGS precipitation gages
Major Streams
Precipitation in inches
0-2
2-4
4-6
6-8
8-10
10-12
12-14
14-16
16-18
Rainfall in inches, measured at USGS gages, September 11 through 22, 2009
in the Atlanta, Georgia Area - Provisional data

Figure 8 Cumulative rainfall totals around Atlanta, Georgia, during the September 2009 floods. Source: USGS.

around Atlanta, Georgia. More research and more robust hypotheses are required to explain how urban attributes contribute to the noninductive charge separation process (Yair 2008). In this process, graupel–ice crystal collisions in the presence of supercooled liquid water and vertical air currents allow for the accumulation and transfer of negative and positive charges throughout the cloud. Logical questions might center around how urban aerosols might delay the onset of precipitation and lead to a more invigorated, glaciated cloud, as Rosenfeld et al. (2008) argued, and how convective forcing associated with the roughness, UHI, and destabilized urban atmosphere increase the likelihood of convective activity. However, the role of aerosols is strongly supported by a few studies. Stallins et al. (2006) found smaller percentages of positive flashes downwind of long sections of major transportation arteries in Atlanta, Georgia. They argued that the aerosol effect may be detectable ~100 km downwind of the Atlanta central business district. Steiger and Orville (2003) observed higher flash densities and lower percentages of flashes in a Lake Charles–Baton Rouge Louisiana corridor. Of interest, this region has significant aerosol-producing refineries and chemical production facilities but not necessarily a centralized urban landscape footprint. For locales devoid of significant land cover, the spatial association among aerosols, increased flash densities, and decreases in the percentage of positive flashes support a mechanistic role for atmospheric particulate matter.

5.07.5.4 Winter Precipitation

Though very limited and not contemporary, early research on urban effects on snowfall suggested that modified freezing rainfall and snowfall occur over and downwind major US cities because of the UHI (Landsberg, 1981; Changnon, 2003). Molders and Olson (2004) have suggested that snowfall anomalies in Fairbanks may be due to urban effects. Other studies of snowfall enhancement downwind of urban areas have been limited and generally focused on aerosol effects (e.g., Van den Berg 2008; Wood and Harrison 2009). Very little work on urban landscape shape and snowfall response exists because the vast majority of research in the physical geography and urban climate literature has posited that urban affects are most apparent during the warm season when smaller scale convective forcing is dominant (Shepherd et al. 2010a; Bentley et al. 2010; Mote et al. 2007). However, Shepherd and Mote (2011) recently argued that enough preliminary evidence is found in the literature to warrant new research on this topic. Clearly, the example quoted in the Section 1 establishes that humans can modify snowfall.

5.07.6 What Causes the URE?

Even with the uncertainties about the 'sign' of the change in precipitation due to urbanization, it is widely accepted that urban environments 'affect' rainfall processes. Shepherd et al. (2010a) stated that "though several plausible hypotheses for urban effects on rainfall have emerged within the literature, there is no conclusive theory on what mechanisms, independently or synergistically, affect urban rainfall processes. A large body of literature has been devoted to pattern description and visualization. These methods are vital for generating and testing these hypotheses, but emphasis has now shifted to documenting

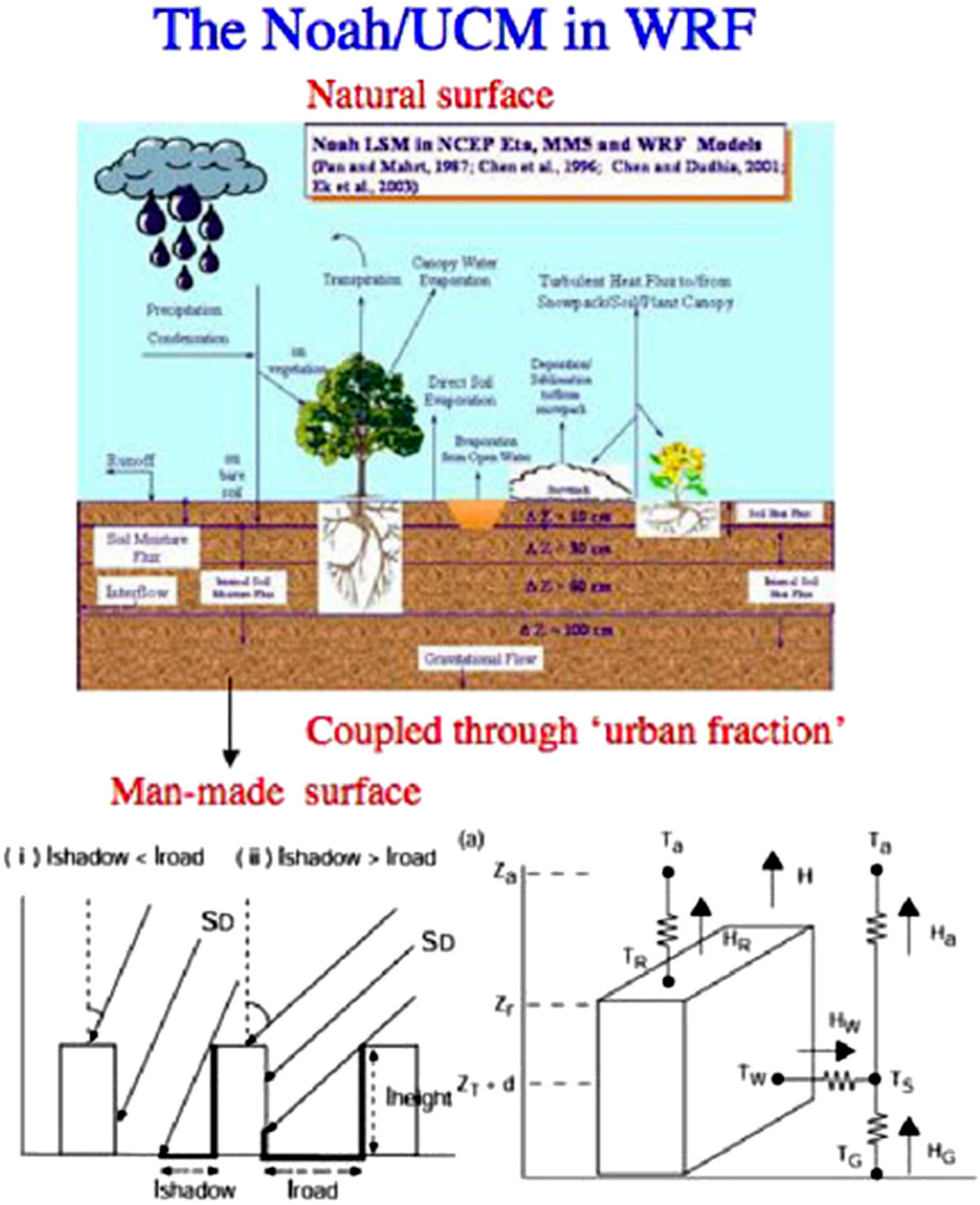
The Noah/UCM in WRF
Natural surface
Noah LSM in NCEP Eta, MM5 and WRF Models
(Pan and Mahrt, 1987; Chen et al., 1996; Chen and Dudhia, 2001; Ek et al., 2003)
Precipitation
Condensation
on vegetation
Transpiration
Canopy Water Evaporation
Turbulent Heat Flux to/from Snowpack/Soil/Plant Canopy
Direct Soil Evaporation
Deposition/ Sublimation to/from snowpack
Evaporation from Open Water
Runoff
on bare soil
Soil Moisture Flux
Interflow
Internal Soil Moisture Flux
Soil Heat Flux
Internal Soil Heat Flux
Gravitational Flow
ΔZ = 10 cm
ΔZ = 30 cm
ΔZ = 60 cm
ΔZ = 100 cm
Coupled through 'urban fraction'
Man-made surface
(i) lshadow < lroad
(ii) lshadow > lroad
SD
SD
lheight
lshadow
lroad
(a)
Za
Zr
ZT + d
Ta
Ta
H
HR
TR
Ha
HW
TW
TS
TG
HG

Figure 9 Example of a couple atmosphere–land–urban modeling systems. Source: UCAR.

mechanisms and elucidating relative contributions (Teller and Levin, 2008)." While some questions remain about the 'URE', the topic has received considerable attention recently.

While mechanistic studies have been precise for single case studies, a larger hydroclimatological perspective covering many years and processes is still needed (Shepherd et al. 2010a). However, it is still useful to highlight the leading hypothesis even though one cannot make generalizations about when they are most applicable.

5.07.6.1 Low-Level Dynamical and Flux Processes

Pielke et al. (2007) is a clear reminder that land cover can influence atmospheric processes. These processes are manifested at the surface, boundary layer (Oke 1987), and beyond. However as Lowry (1998) noted, controlled experiments are required. One of the most appropriate 'laboratories' for assessing mechanisms is the physically based CALS model. CALS enables a plausible way to remove or alter land surface, aerosol, topographic, or meteorological features to evaluate atmospheric responses under different scenarios. Figure 9 summarizes how the CALS model interacts to characterize thermodynamic, dynamic, and moisture exchanges.

Post-METROMEX era model experiments provided early evidence that the URE was linked to urban-induced convergence, thermodynamic changes, and surface fluxes. Table 2 summarizes some of the key findings from the period 1979 to 2011.

A common weakness of the studies in Table 2 is the lack of representation of aerosols or pollution. This is somewhat a function of the state of the modeling technology, but next-generation modeling systems are starting to address this deficiency. van den Heever and Cotton (2007) considered urban landscape and aerosol effects in their modeling study of St. Louis. More of these types of studies are required to determine the relative roles of aerosols in the URE.

5.07.6.2 Aerosol Roles

Aerosols are defined in Shepherd et al. (2010a) as "particles in the atmosphere, ranging from 0.01 μm to 10 μm. Urban regions usually have the highest concentration of aerosols, up-to 108–109 particles per cc (Seinfeld and Pandis, 1998). Aerosols can be divided by size: fine mode and coarse mode particles. Coarse particles are composed of mechanical materials such as tire dust, sea salt and natural dust in urban areas. Fine particles tend to be produced locally by construction, air conditioning, transportation, and industry or by chemical interactions [in the atmosphere] involving sulfates, nitrates, ammonium and organics."

Urban aerosols can vary in composition: black carbon, particulate matter, sulfates, nitrates, and others. The direct radiative effect of aerosols scatters or reflects solar radiation. Jin et al. (2011) recently presented evidence that aerosol direct effects can significantly reduce the magnitude of the urban skin temperature heat island, which may in turn affect precipitation processes. Some aerosols, mainly black carbon, may absorb and warm the atmosphere, which may have a large-scale stabilization effect on the atmosphere, thus suppressing cloud

Table 2 Key model studies over the period 1978 to 2011

Authors	*Key finding*
Vukovich and Dunn (1978)	Urban–rural gradients and boundary layer stability primarily describe UHI mesocirculations, which are conceptually similar to sea-breeze circulations
Huff and Vogel (1978)	Sensible heat fluxes and surface roughness associated with urban surfaces transport heat to the atmosphere
Hjelmfelt (1982)	Rising motion linked to St. Louis-induced low-level convergence/translation of the urban circulation by larger-scale advection. Bornstein and Lin (2000) later corroborated this finding by using a special observation network in Atlanta
Thielen et al. (2000)	Weak UHIs are associated with sensible heat flux, buoyancy, and convergence variations at a distance from heat source
Rozoff et al. (2003)	Nonlinear interactions associated with momentum drag, urban surface friction, and heating could induce downwind converge
Niyogi et al. (2006)	Applied urban canopy models embedded in the land surface model. Such models represent 3D urban morphology and heterogeneity rather than simple slab representations of urban surface. Their simulations demonstrated how the urban morphology affects temperature and wind flow
Gero and Pitman (2006)	Dynamical forcing (increased instability and convergent forcing) triggered a convective storm over urban land cover associated with Sydney, Australia
Ikebuchi et al. (2008)	Confirmed that urban land cover and anthropogenic heating altered the location and intensity of convective rainfall around Tokyo
Baik et al. (2007) and Han and Baik (2008)	Used numerical and analytical models to show that boundary layer destabilization leads to a region of intensified rising motion induced by the UHI. These studies also offered a plausible explanation for why urban convective effects can be apparent in the daytime even though UHI magnitude is greater in nocturnal hours (Arnfield, 2003). They reasoned that during daytime hours, stability conditions favor stronger UHI circulations. Han and Baik (2008) also found, using a 3D framework, an internal gravity wave field with a rising branch downwind of the theoretical heat source (e.g., the city)
Shem and Shepherd (2009)	Combined urban-induced convergence associated with urban circulation on the perimeter of Atlanta's urban land cover and increased sensible heat flux contributed to enhancement of convection in Atlanta case studies
Shepherd et al. (2010b)	Enhanced sensible heat flux and low-level convergence associated with urban land cover interacts with sea-breeze circulation near Houston to create regions favorable for convective development. Carter et al. (2012), Lo et al. (2007), Yoshikado (1994), and Ohashi and Kida (2002) have found similar results for Houston, Hong Kong, and Japanese cities. Shepherd et al. (2010b) also used 2025 urban land cover projections to determine future precipitation changes as a function only of land cover change (no greenhouse gases)
Niyogi et al. (2011)	Indianapolis' urban land cover modifies convective system structure, pathway, and intensity

development (Kaufman et al. 2005). However, this aspect of the urban rainfall problem warrants further study.

The indirect effect of aerosols (i.e., aerosols serve as CCN) on precipitation has received most attention in the literature. Twomey (1977) posited that under the condition of finite water vapor availability, more CCN will lead to more competition for water vapor in the cloud–droplet formation process. This process leads to smaller cloud droplets that are not able to grow efficiently or rapidly to produce raindrops. Jin and Shepherd (2008) employed satellite-derived cloud, aerosol, and precipitation properties to confirm the Twomey effect over regions of China and adjacent maritime regions.

The literature is rich with recent discussions on how aerosols affect precipitation (Rosenfeld and Lensky 1998; Rosenfeld 2000; Givati and Rosenfeld 2004; Kaufman et al. 2005; Jin et al. 2005; Lensky and Drori 2007; Rosenfeld et al. 2008; Jin and Shepherd 2008; Stjern et al. 2011; Lin et al. 2011). The prevailing understanding is that larger maritime aerosols enhance the collision–coalescence process, promote larger droplets, and create earlier rainout. On the other hand, smaller aerosols over land counter the collision–coalescence process. This may delay rainout and invigorate the cloud to deeper convection (Rosenfeld et al. 2008). This scenario suggests that suppressed precipitation by urban aerosols (Lin et al. 2011) might be associated with increased electrification and rainfall intensification. Figure 10 presents a summary of such processes and illustrates how suppressed rainfall might lead to an invigorated convective cloud and more electrification. It should be noted, however, that many of the aerosol studies have not focused on urban aerosols and more work is required because there is still a great degree of uncertainty (Stjern et al. 2011).

5.07.6.3 Bifurcation and Other Dynamic Effects

As noted earlier, the presence of buildings, the thermodynamic UHI dome, or a combination of the two can modify local and regional circulations around cities. Both observational and modeling studies continue to confirm that convective cells can be redirected, bifurcated, or altered by the urban landscapes.

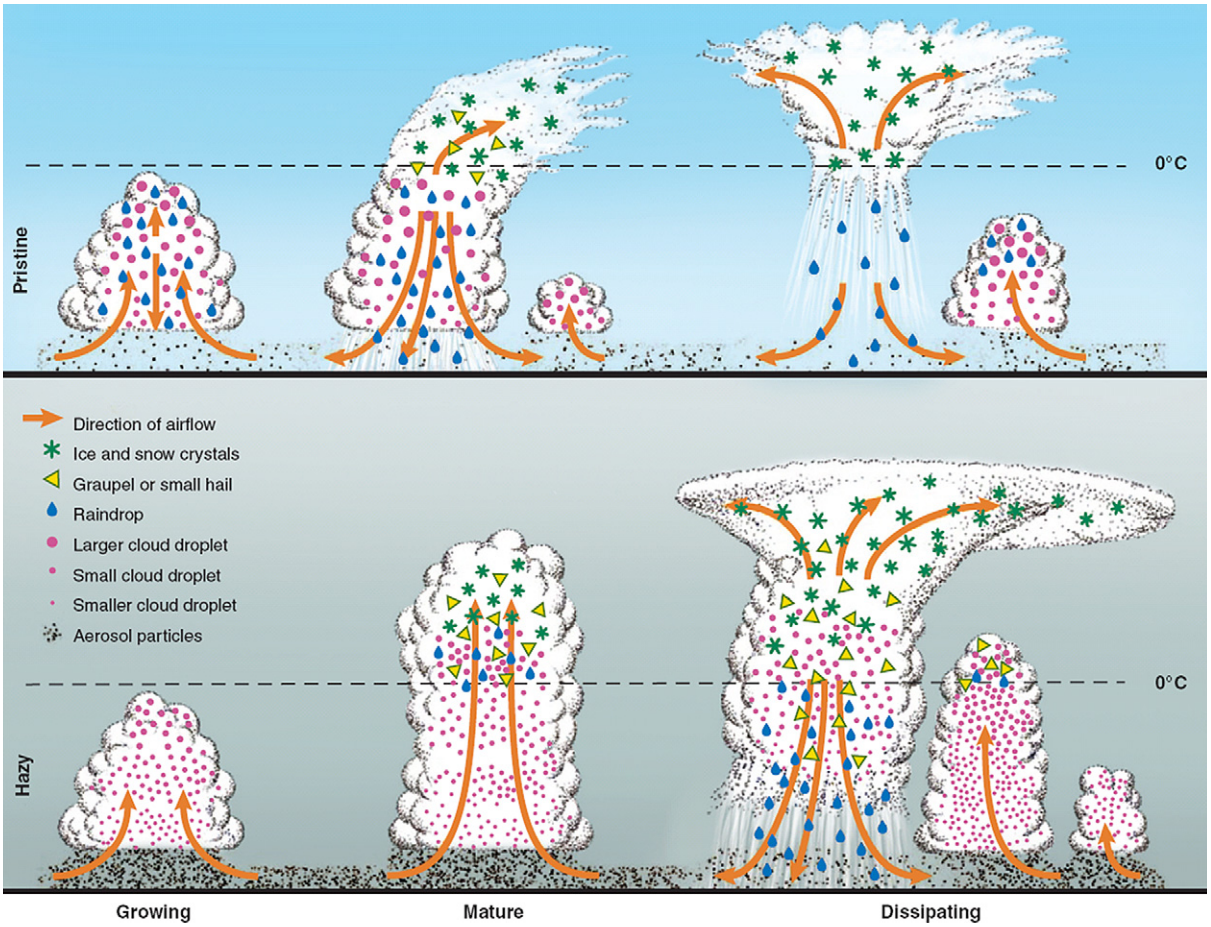

Figure 10 Evolution of deep convective clouds developing in the pristine (top) and polluted (bottom) atmosphere. Cloud droplets coalesce into raindrops that rain out from the pristine clouds. The smaller drops in the polluted air do not precipitate before reaching the supercooled levels, where they freeze onto ice precipitation that falls and melts at lower levels. The additional release of latent heat of freezing aloft and reabsorbed heat at lower levels by the melting ice implies greater upward heat transport for the same amount of surface precipitation in the more polluted atmosphere. This means consumption of more instability for the same amount of rainfall. The inevitable result is invigoration of the convective clouds and additional rainfall, despite the slower conversion of cloud droplets to raindrops. Reproduced from Rosenfeld, D., U. Lohmann, G. B. Raga, C. D. O'Dowd, M. Kulmala, s. Fuzzi, A. Reissel, and M. Andreae, 2008: Flood or drought: How do aerosols affect precipitation? *Science*, **321** (5894), 1309–1313.

Bornstein and LeRoy (1990) argued that the building barrier effect caused storms to bifurcate around New York City. Stallins and Bentley (2006) observed peaks in flash density in air mass thunderstorms on the periphery of the urban core, and the highest flash densities were associated with the urban core. Ntelekos et al. (2007) argued that the Baltimore–Washington, DC, corridor influenced the movement of storms and associated outflow boundary. Shear instability (i.e., turbulence related to differential wind velocity in the vertical) and diurnal heating can also force horizontal convective rolls in urban areas (Miao and Chen 2008). Niyogi et al. (2011) argued that storms were commonly altered by the urban landscape of Indianapolis, Indiana. Such structural changes included splitting, enhancement, and downwind mergers. Further research must shed light on whether a building, thermodynamic boundary layer, or combined barrier effects lead to such dynamical responses. It is even interesting to speculate on how the urban environment affects severe weather (e.g., tornadoes). Do such barrier effects explain the lack of tornado strikes in central business districts or is simply a function of scale? One might also posit whether the thermodynamic and moisture environments of a city can affect inflow at convective scales in severe environments (Jeff Basara, 2010, personal communication).

Bornstein (2011, personal communication, with modifications by S. Grimmond and M. Shepherd) attempted to provide a framework for understanding urban thunderstorm effects (Figure 11). This conceptual schematic is based on several years of research and captures some of our understanding. However, this schematic will evolve as our understanding improves.

5.07.7 Broader Context

An array of related studies continues to emerge related to urban rainfall processes. HYPERLINKvan den Heever and Cotton (2007) important study noted that urban-induced wind convergence determined storm initiation in their simulations, but aerosols influenced the amount of cloud water and ice present in the clouds. Also, aerosols were important determinants of the updraft and downdraft intensities, their life span, and surface precipitation totals. Shepherd et al. (2001) investigated rainfall efficiency in sea-breeze thunderstorms and is a nice analog to the van Den Heever and Cotton study's discussion of integrated moisture convergence (initiating the storms) and mid-level moisture (affecting the rainfall efficiency). Such synergistic modeling/observational studies that capture aerosol and urban landscape sensitivities are critically needed. Bell et al. (2008) have presented evidence of a weekly precipitation cycle over the southeastern United States that may be linked to an anthropogenic aerosol cycle. However, other studies refuted the notion of a weekly cycle (i.e., DeLisi et al. 2001; Schultz et al. 2007; Lacke et al. 2009).

Several mitigating factors constrain the expression of aerosol, thermodynamic, and surface roughness mechanisms. Such factors include topography, aerosol concentrations, or seasonality. Studies must continue to detangle these influences from any attribution studies on the URE (Shepherd et al. 2010a). Other key mitigating factors are the shape, the form, and the size of cities. METROMEX suggested that large urban areas are more likely to be associated with the URE. Yet, there is very little research (observational or modeling) on threshold sizes for cities, optimal city shapes, and the role of morphology in relation to urban rainfall anomalies.

In summary, urban environments are clear examples of how the human system can modify the natural system in terms of weather and climate. The more this complex system is understood, the better the system and optimize interactions in the coupled system can be predicted. More importantly, the ability to anticipate and manage an array of natural and societal vulnerabilities can also be improved.

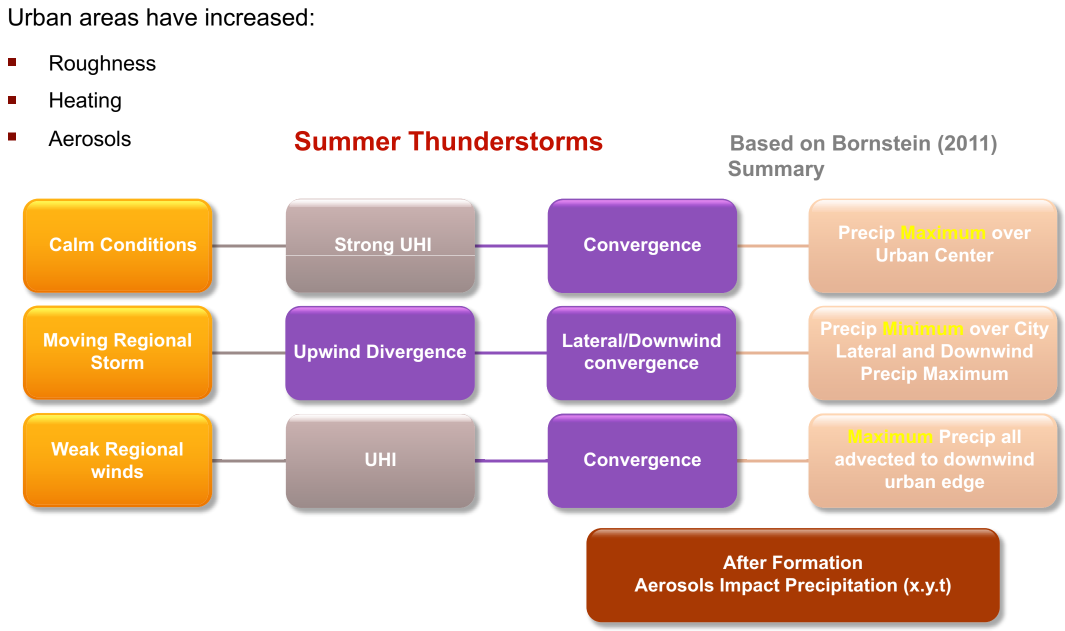
Urban areas have increased:
Roughness
Heating
Aerosols
Summer Thunderstorms
Based on Bornstein (2011) Summary
Calm Conditions
Strong UHI
Convergence
Precip Maximum over Urban Center
Moving Regional Storm
Upwind Divergence
Lateral/Downwind convergence
Precip Minimum over City Lateral and Downwind Precip Maximum
Weak Regional winds
UHI
Convergence
Maximum Precip all advected to downwind urban edge
After Formation Aerosols Impact Precipitation (x.y.t)

Figure 11 Summary of urban effects on thunderstorms (courtesy of B. Bornstein).

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5.08 Analysis of Paleoclimate Records for Understanding the Tropical Hydrologic Cycle in Abrupt Climate Change

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5.08.1 Introduction

The Dansgaard–Oeschger (D/O) warming and cooling cycles, first described from Greenland ice cores (Dansgaard et al. 1993), are one of the most remarkable and precise pieces of evidence for large-magnitude abrupt climate change, Abrupt climate change is used in this context to mean "abrupt changes in the statistics of important components of the climate system." In their landmark report, National Research Council (2002) provided two definitions: the 'physical' definition: a transition of the climate system from one regime into a distinctly different one, on a timescale that is faster than the responsible forcing. There is also the societal or ecological definition: a climate change that takes place so rapidly and unexpectedly that human and natural systems have difficulty adapting to it during the last glacial period (between 80 and 10 ka). The period of these cycles range from 5 to 10 kyr and are associated with an abrupt temperature increase as large as 20–25 °C (Huber et al. 2006), mostly around the North Atlantic and Western European regions. These temperature changes occurred rapidly within a single decade and lasted for several decades. These cycles are also documented in marine sediment archives. D/O cycles are terminated by Heinrich massive iceberg rafting events with a period of 7.2 kyr from the late Pleistocene Laurentide ice sheet (LIS) (Bond et al. 1993; Rashid and Boyle 2007), mostly over Canada (Hemming et al. 1998). The release of cold freshwater by melting of icebergs is thought to be the link between these rapid temperature increases and abrupt climate change. Introduction of this freshwater to the surface of the North Atlantic is assumed to limit the formation of North Atlantic Deep Water (NADW) in the Norwegian-Greenland seas, and prevented the penetration of the North Atlantic Drift (the northern branch of the Gulf Stream) into higher northeastern latitudes. As a result, the Atlantic meridional overturning circulation (AMOC) is weakened, resulting in the transport of less warm water and a subsequent weaker exchange of moisture from the tropics to high northern latitudes. In contrast, the Gulf Stream transports enormous amounts of heat, maintaining a warmer northwestern Europe, and provides a stronger ocean–atmosphere exchange of moisture during warm stadials when the AMOC is strong.

The impact of these warm–cool D/O cycles was not restricted to the North Atlantic Ocean and the surrounding region; it also extended to the tropical regions, as evident in numerous terrestrial and marine paleoarchives (Clement and Peterson 2008; and references therein). The paleoclimatic records from the northern tropics and subtropics show climate changes concordant with those of the North Atlantic and Greenland, while asynchronous and even negatively correlated phenomena are exhibited in records from the southern tropics and high latitudes of the Southern Hemisphere. For example, the Indian and East Asian monsoon systems appear to positively correlate with the North Atlantic climate, whereas the South American monsoon records show anticorrelation with the Greenland records (Wang et al. 2006). One of the most important effects of the D/O cycles on past climate is their strong spatial variation on the tropical hydrological cycle that caused some parts of the tropics to remain dry while others remained wet. This synthesis provides an overview of the tropical hydrological cycle in the context of abrupt climate change during the last glacial–interglacial cycle. The modern tropical hydrological processes are first discussed followed by a description of a broad tropical paleohydrological cycle perspective during the glacial–interglacial cycle with dynamical underpinning on the African continent, Indian subcontinent, and southeast Asian regions. After exploring the climate scenarios in the modern and glacial perspective, three time slices are discussed at length: the Last Glacial Maximum (LGM; a time window between 24 and 18 ka), the Early Holocene (10–6 ka), and the Late Holocene (5 ka to present) periods. Finally, a perspective on the role of the tropical hydrological changes in modulating ancient civilizations of the Indian subcontinent and NE China is provided.

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5.08.2 Modern Tropical Hydrological Cycle

The tropics lie between 30° N and 30° S latitudes, encompassing 50% of the Earth's surface area. Variations occurring here have a tremendous impact on global climate and are associated on an interannual timescale with phenomena such as the Asian monsoon, on a global scale with the El Nino–Southern Oscillation (ENSO), and on millennial timescales with tropical paleoclimate. Home to 70% of the world's 7 population, the region is at the center of the global hydrological cycle and drives the Earth's atmospheric and oceanic circulations and is therefore a fundamental component of global climate dynamics (Cane 1998; Webster et al. 1998; Clift and Plumb 2008). The tropical hydrological cycle describes the continuum of movement of water between the atmosphere, surface, and within the subsurfaces of the earth. The primary components of the hydrological cycle are atmospheric precipitation and terrestrial evaporation. But the distribution of tropical rainfall, hence the tropical hydrological cycle, is not uniform all over the tropics (Chiang 2009); rather, it is centered on specific regions (Figure 1(a)). The atmosphere stores a very small fraction of water relative to the oceans with a significantly shorter residence time, and therefore yields less information regarding past hydrological cycles. Its role as a transport medium is by far more important than its storage capacity, thus imbalances in the hydrological cycle are usually best depicted on land and in the ocean. Paleoclimate records show changes in lake levels, oceans, and discharge from rivers. While the amount of water stored in polar ice sheets (Greenland and Antarctica), high-altitude but low-latitude ice caps, and subsurface layers is enormous, changes in these reservoirs occur on very long timescales and are usually ignored in most discussions of the hydrological cycle. Insolation has varied in the past (Berger and Loutre 1991) and provides the energy driving the hydrological

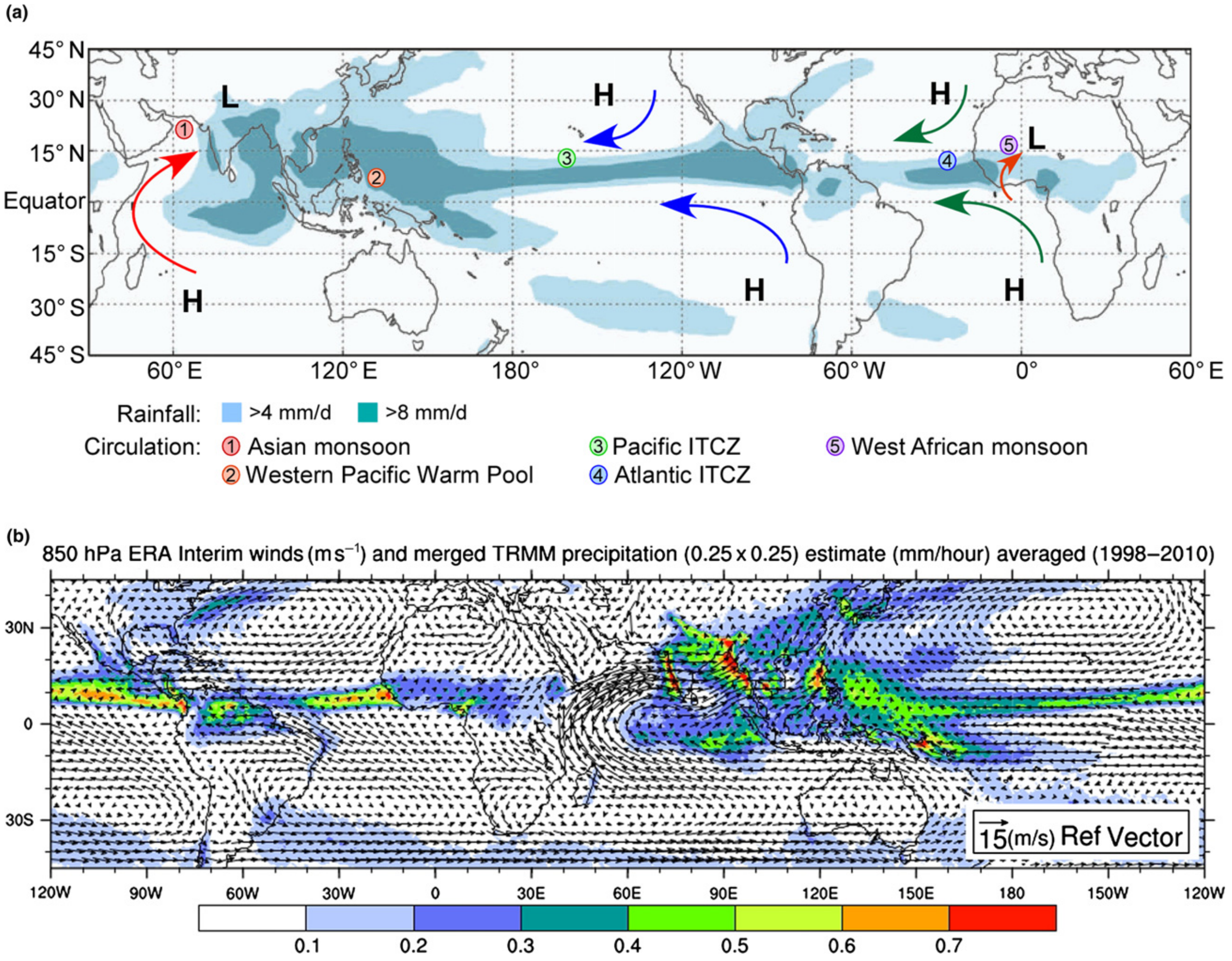
(a)
45° N
30° N
15° N
Equator
15° S
30° S
45° S
60° E
120° E
180°
120° W
60° W
0°
60° E
L
H
H
L
H
H
H
①
②
③
④
⑤
Rainfall: >4 mm/d >8 mm/d
Circulation: ① Asian monsoon ② Western Pacific Warm Pool ③ Pacific ITCZ ④ Atlantic ITCZ ⑤ West African monsoon
(b)
850 hPa ERA Interim winds (m s⁻¹) and merged TRMM precipitation (0.25 x 0.25) estimate (mm/hour) averaged (1998–2010)
30N
0
30S
120W
90W
60W
30W
0
30E
60E
90E
120E
150E
180
150W
120W
15(m/s) Ref Vector
0.1
0.2
0.3
0.4
0.5
0.6
0.7

Figure 1 (a) Tropical climate from a regional perspective. The figure shows July–August climatological rainfall conditions and surface winds (arrows) depicting circulations associated with the Asian (2) and West African (5) monsoons, as well as the subtropical trades flowing into the Intertropical Convergence Zone (ITCZ) regions of the Pacific (2) and Atlantic (4); (5) is the conversion over the Western Pacific Warm Pool. L and H denote locations of relative surface pressure lows and highs. (b) July average (13 years) tropical precipitation (millimeters per hour) from National Aeronautics and Space Administration's (NASA) Tropical Rain Measuring Mission (TRMM) and corresponding ERA Interim reanalysis winds (meters per second) from the European Center for Medium-Range Weather Forecast (ECMWF) for the modern climate (Dee et al. 2011). The scale for the winder vectors is indicated by reference vector (top). Modified after J. C. H. Chiang, 2009: The tropics in paleoclimate. *Annu. Rev. Earth Planet. Sci.* **37**, 263–297.

cycle. The tropics therefore have the capacity to influence the global hydrological cycle on millennial timescales and also provide evidence to study past climate (Cane 1998).

The prevailing view is that warm tropical temperatures primarily enhance sea-surface evaporation, providing the primary input to the atmospheric part of the hydrological cycle. The moisture-laden air is then transported in the rising branches of the Hadley Cell to the extra tropics taking along with it the latent energy absorbed in the tropics. Beyond the Hadley Cell in the extra tropics, transport by transient eddies is significant and can be enhanced during periods of increased meridional temperature gradients between the tropics and the extra tropics (e.g., LGM). Because of the close connection between tropical rainfall and insolation, the temporal variations in tropical rainfall are generally explained by the seasonal migration of the Intertropical Convergence Zone (ITCZ) of the trade winds from an air mass dividing the trade winds from both hemispheres (**Figure 1(b)**). Tropical convection resulting from this convergence tends to concentrate over land masses, the maritime continent of the western Pacific Ocean, and also tropical Africa and South America. Over the Pacific and Atlantic Oceans, northeasterly and southeasterly trades are driven from the high surface pressures in the subtropics toward the low-pressure regions near the equator. Migration of the ITCZ is not uniform over the entire tropics and shows a wide range over East but not West Africa (**Figure 1(b)**), and only a narrow band of rainfall associated with the ITCZ is found in the tropical Pacific in spite of a large oceanic expanse.

The heaviest and most widespread precipitation occurs in the region of the Asian monsoon and does not fit this classic definition involving interhemispheric convergence or migration (**Figure 1**). It is thought that the Qinghai-Tibetan Plateau plays a significant role possibly through topographically induced uplift or convergence of moist air from the Indian Ocean over the Northern Hemisphere summer thermal low that forms over Tibet (**Figure 2**) (Webster et al. 1998; Ratna et al. 2011). Rainfall over the Indian subcontinent and southeast Asia is seasonal but usually associated with a seasonal reversal of winds over the Indian Ocean rather than the convergence of trade winds from the Northern and Southern hemispheres. The thermal low induces a cross-equatorial flow that brings rain-bearing winds into the region. Since coastal monsoon rains act to diminish the sensible heating of the atmosphere (as the heat capacity of the wetted land surface rises), the zone of maximum vertical velocity, and therefore precipitation, will migrate inland to hotter, drier ground. The result is continued pulses of intense rainy periods (active phase) followed by hot, dry conditions (dormant phase) throughout the summer monsoon season, cycling over a roughly 2-week period (**Figure 2**). This precipitation supports nearly a quarter of the Earth's population, hence its significance to civilizations in these regions. More recently, as the underlying mechanisms have come to be better understood, other regions showing an annual climatic cycle with seasonal wind reversals resulting in wet summers and dry winters have also been labeled as monsoonal climates (Webster, 1981; Webster et al. 1998; Rashid et al. 2007). These areas include a large portion of southeast Asia, central Africa, and northern Australia, which are out of phase with the Indian monsoon because of their location in the Southern Hemisphere (Clift and Plumb 2008) (**Figure 1**). A similar but weaker monsoon dynamics exists over West Africa (Chiang 2009). North African precipitation is limited to the southern margins of the Sahara desert, with higher values in the Congo Basin (**Figure 1**). Therefore, variations in lake levels and river discharge provide evidence for past variations in the tropical hydrological cycle in Africa. A precipitation maximum similar to that of Congo is also found over the Amazon Basin in South America. Changes in precipitation across the tropical belt are thought to be linked via the global Walker Circulation. A zonal shift in this circulation can therefore cause drying in one area of the tropics while enhancing precipitation in another and may explain the coherent response from North tropical Africa to East Asia (as discussed in Section 5.08.3). Therefore, while uniform proxies may not be available across the entire tropical belt, changes in precipitation indicated by one proxy in one region can be strongly correlated with other proxies in other regions.

5.08.3 Tropical Paleoclimate during the Last Glacial–Interglacial Cycle

The modern tropical hydrological cycle described earlier weakened during the last glacial–interglacial cycle (including the LGM) (Mix et al. 2001). Oxygen isotopic ratios ($^{18}O/^{16}O$: expressed as $\delta^{18}O$) in ice cores from the Guliya Ice Cap of northwest China (**Figure 3(e)**) show a more negative $\delta^{18}O$ values and are interpreted as a decrease in the amount of moisture being transported in summer during a colder climate. In contrast, less negative $\delta^{18}O$ values are interpreted as a sign of increase, suggesting a stronger moisture transport during warmer conditions. The $\delta^{18}O$ values from the northwestern Tibetan Plateau at an altitude of 6.7 km (above sea level) are higher, suggesting wetter conditions over the Indian Subcontinent, which can be associated with dramatic increases in the strength of the Westerlies (Barnett et al. 2005). Although the $\delta^{18}O$ were generated from a location that is thousands of kilometers away from the North Atlantic realm, records show a remarkable similarity to the Greenland $\delta^{18}O$ records and are postulated to be teleconnected. Data from the Shanbao and Hulu caves in the northeastern Chinese Plain (approximately at sea level) also show a $\delta^{18}O$ pattern similar to that of the Greenland core (Wang et al. 2005). $\delta^{18}O$ in calcite deposits (known as speleothems) show similar high and low values (**Figure 3(b)**) during the D/O cycles for the last glacial–interglacial cycle. This is interpreted as weaker and stronger Asian monsoon, respectively, reflecting a dramatic reduction and intensification of the hydrological cycle in only a matter of decades.

However, the reduction in the hydrological cycle is not uniform on both sides of the equator. Paleohydrological records from South America also show dramatic changes in rainfall, as revealed in speleothem archives. One such highly resolved terrestrial climate record from Caverna Botuvera, southern Brazil is shown in **Figure 2(c)** (Wang et al. 2006). This Southern Hemisphere subtropical site shows high $\delta^{18}O$ values (interpreted as dry periods, weak monsoon, and less rainfall) (**Figure 3(b) and 3(c)**) in sharp contrast to the low $\delta^{18}O$ values of the Shanbao and Hulu caves of northeastern China

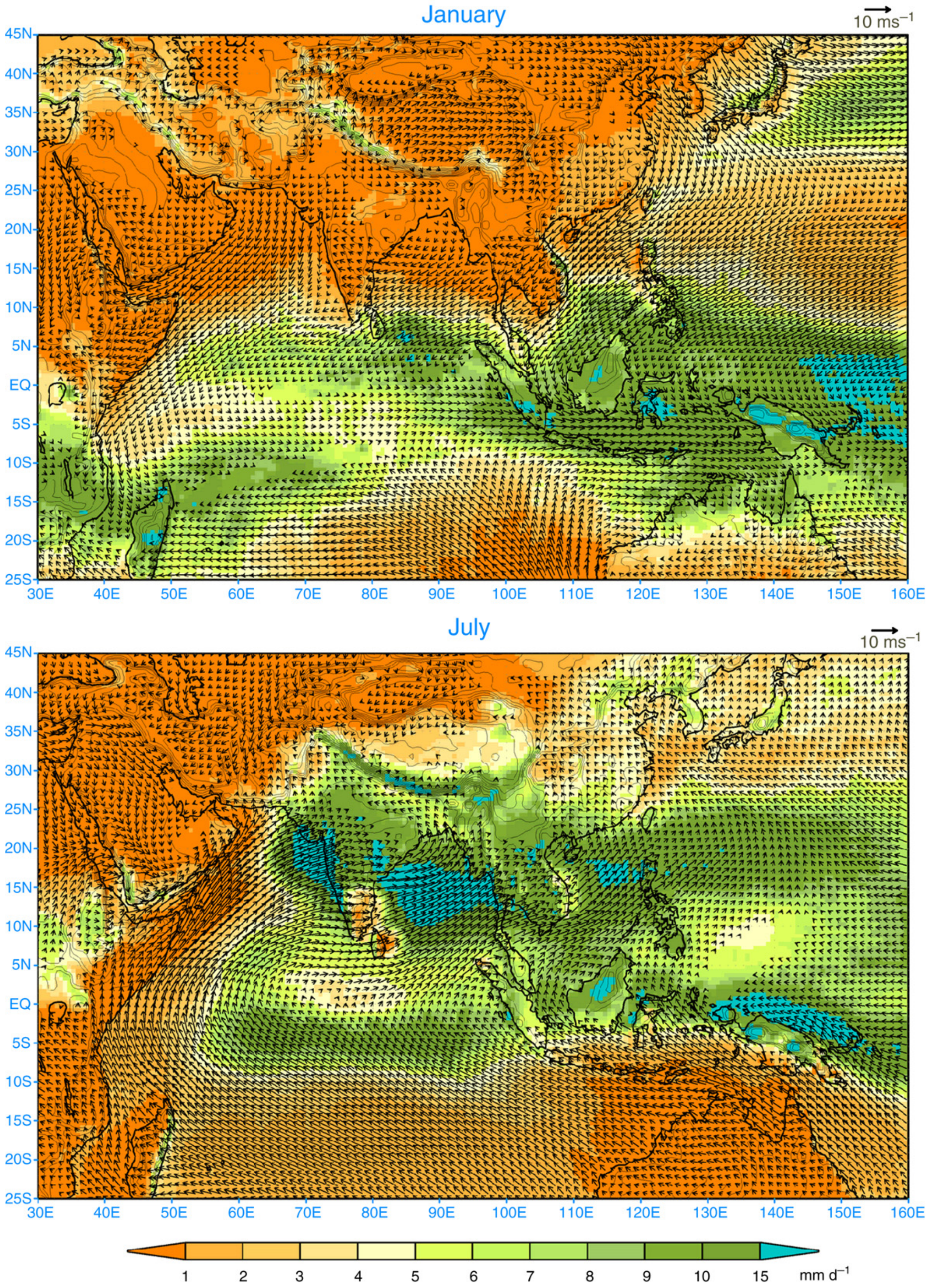
January
10 ms^{-1}
45N
40N
35N
30N
25N
20N
15N
10N
5N
EQ
5S
10S
15S
20S
25S
30E
40E
50E
60E
70E
80E
90E
100E
110E
120E
130E
140E
150E
160E
July
10 ms^{-1}
1
2
3
4
5
6
7
8
9
10
15
mm d^{-1}

Figure 2 Modern Indian monsoon system (Lau and Nath 2012). Output from several simulations based on atmospheric GCMs with spatial resolution in the 25–50 km range, which were compared with available observations of comparable resolution, such as satellite data. Particular attention has been devoted to regional details of the diurnal cycle and fine structure of mesoscale meteorological systems (Lau and Nath 2012). [Available online at http://www.gfdl.noaa.gov/gabriel-lau-homepage.]

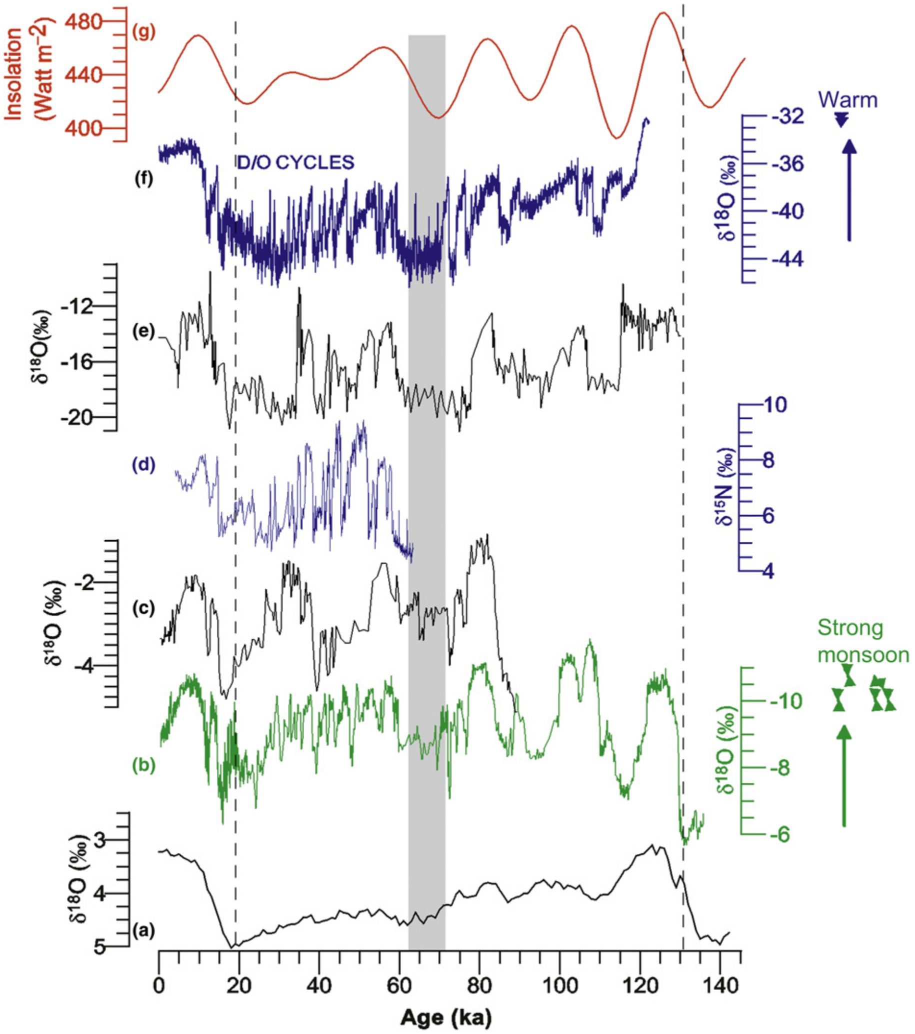

Figure 3 Proxy records that demonstrate abrupt climate changes during the last glacial cycle from various paleoarchives. (a) Global stack of benthic foraminiferal oxygen isotopes ($\delta^{18}O$) (Lisiecki and Raymo 2005) provides chronology of climate events; (b) and (c) $\delta^{18}O$ in the Shanbao and Botuvera speleothems from northeast China and Brazil, respectively (Wang et al. 2006); (d) $\delta^{15}N$ from the Arabian Sea (Atlabet et al. 2002); (e) and (f) $\delta^{18}O$ in the Guliya (NW Tibetan Plateau) and Greenland NGRIP ice cores with revised chronologies (Svensson et al. 2008; Rashid et al. 2011); and (g) June insolation at 65° N (Berger and Loutre 1991). All records are plotted according to their independent age models. Note that the vertical gray bar indicates the duration of Marine Isotope Stage (MIS) 4 (62–74 ka), and the two vertical dashed lines indicate the 20- and 130-ka time horizons.

(interpreted as wet periods and hence intense Asian monsoon and high rainfall) in the Northern Hemisphere. The modern climate of Caverna Botuvera is largely affected by the South American monsoon. When the monsoon dominates during the austral summer season, equatorial trade winds transport moisture from the tropical Atlantic toward the Amazon Basin. Owing to the blocking effect of the Andes, warm and humid air is forced to veer to the southeast, developing deep convection over central and southern Brazil. The antiphased precipitation relationship between eastern China and South America, equivalent tropical regions on either sides of the equator thousands of kilometers apart, reverses during the D/O cycles (**Figure 3(b) and 3(c)**). This antiphasing precipitation dynamics is explained by the north–south shifts in the mean position of the ITCZ and asymmetry in Hadley circulation in both hemispheres. These fluctuations were not associated with seasonal changes as observed today, but with millennial-scale climate shifts. The millennial-scale atmospheric seesaw patterns observed in the Brazilian cave records (**Figure 3(c)**) could have important controls and feedbacks on the climate within hemispheres because of greenhouse properties associated with water vapor (Wang et al. 2006).

Rapid changes in the tropics were also reported from many marine sediment archives, including large fluctuations of biological productivity in surface layers of the ocean. For example, an abrupt fluctuation in the δ^{15} N total organic carbon (TOC) in marine sediments from the Arabian Sea were correlated to the D/O cycles of Greenland (Altabet et al. 2002). The nitrogen isotopes systematics is such that the marine bacteria typical of oxygen-depleted zones preferentially use nitrogen-14 when converting marine nitrates (dissolved NO_3^-) into gaseous nitrogen (N_2O and N_2), leaving the remaining NO_3^- enriched in ^{15}N. Measurements of the $^{15}N/^{14}N$ in organic matter preserved in ocean sediments can thus be used to track changes in the denitrification processes that are usually associated with oxygen depletion in the ocean. It is interesting that the weakening of biological activity in the Arabian Sea fits nicely with the weakening of the Asian monsoon (**Figure 3(d)**). In the global ocean, the abruptness in biological activity could be linked to the injection of nutrients into the surface layer by wind-induced mixing and upwelling. An additional cause could be the direct input of biolimiting elements in dust transported by low-latitude winds. In the Arabian Sea records, a sharp reduction in TOC and low δ^{15}N (**Figure 3(d)**) values were related to the reduction in biological productivity due to the weakening of upwelling along the Somali margin. This reduction in upwelling was tied to the decrease in the pressure gradients due to the potential presence of a larger Qinghai-Tibetan ice sheet and/or the presence of perennial snow cover over Eurasia (Kutzbach 1987).

A fair amount of paleoceanographic data is available from the Arabian Sea to understand the mechanisms behind the origin of the Indian summer monsoon (ISM) and the role of moisture in modulating the continental hydrology. Several studies from both the western (Anderson and Prell 1992) and eastern Arabian Sea show that the ISM has been punctuated by millennial- to submillennial-scale abrupt changes. Using TOC (%) and sonic velocity in three cores from the Oxygen Minimum Zone off Pakistan, Schulz et al. (1998) correlated the variability of the biological productivity to D/O-cycles/H-events. The authors suggested that enhanced biological productivity in the eastern Arabian Sea was forced by the strong summer monsoon. Using dust as a proxy for humidity/aridity, it is suggested that low dust content was associated with a humid continental climate and high dust content was associated with dry conditions in the neighboring Arabian Peninsula.

5.08.4 Tropical Climate during the LGM

The LGM represents a period of the greatest extent and height of ice sheets in both hemispheres during late Pleistocene (Broecker and Denton 1990). In addition, ice caps in the lower latitude but high altitude (such as Kilimanjaro, Qinghai-Tibetan Plateau, South American Cordillera, etc.) were most likely larger, and the snowline descended 1 km lower than their current altitude (Broecker and Denton 1990). These altered physiographic configurations greatly modified the temperature gradients between the polar and subtropical latitudes and intensified atmospheric circulation. Furthermore, the atmosphere was cold and dry, resulting in not only reduction in rainfall but also a change in regional redistribution of rainfall. Most paleoproxies seem to suggest that the tropical terrestrial climate was colder than the tropical sea-surface temperatures (Stute and Talma 1998; Mix et al. 2001).

Paleoproxies for various climate indicators from the tropics were plotted for the period between 10 and 22 ka, including the LGM. Among the greenhouse gases, methane is considered important and is directly related to the tropical hydrological cycle. It is known that the tropics are the main source of atmospheric methane today. However, methane was very low (**Figure 4**) during the height of LGM; this is consistent with cooler tropics, which also have reduced rotting of nutrients and release of methane from lakes, compared to those in polar regions. As described earlier, the Indian and Asian monsoons were also weaker during the LGM (Rashid et al. 2007, 2011) (**Figure 4**) as also the African monsoon (Gasse 2000). Calcium in deep marine sediments mainly reflects the biogenic carbonate component, whereas titanium, which is related to siliciclastic sediment components, varies directly with the terrigenous fraction of the sediment. Therefore, maxima in Ti/Ca ratios characterize periods when precipitation in the Brazilian hinterland abruptly increased and erosion and fluvial transport of terrigenous matter to the shelf and continental slope were strongly enhanced. Clay mineralogic and palynologic studies from nearby marine sediment core sites, as well as speleothem and travertine deposits, confirm the occurrence of more humid phases in northeast Brazil (Wang et al. 2006). It is noteworthy that the Ti/Ca ratios suggest an apparent increase in Amazon runoff (**Figure 4(b)**).

5.08.4.1 Lake Level Records

Water levels in closed-basin lakes have been shown (Gasse 2000) to be a meaningful indicator of the precipitation–evaporation balance in the hydrological cycle and hence an indicator of the state of the hydrological cycle during a given climate epoch. To demonstrate the status of the tropical hydrological cycle in the context of LGM, a 30-ka chronology of lake levels from equatorial Africa has been used in **Figures 5 and 6** (Street and Grove 1979; Gasse 2000). A majority of the lakes showed arid conditions beginning ~22 ka, which intensified after the LGM and reached maximum aridity between 15 and 12.5 ka (**Figure 6**). Although the increases in summer insolation have been invoked as the probable cause, a water balance calculation for eastern Africa implied that a reduction in precipitation of 9–40% relative to today was experienced (Dalfes et al. 1997). Wetter conditions arrived shortly thereafter, and 97% of tropical African lakes abruptly reached their maximum levels in the period from 9 to 7 ka. Relict sand dunes across present subtropical deserts of Africa and Asia from the time of LGM show the onset of wetter conditions beginning around 12–10 ka (Kutzbach 1987). In addition, a gradual migration of a 'belt' of high water levels from about 20° N to 30° N over roughly the 2000 years has been cited and attributed to a poleward migration of the ITCZ. Beginning at 4.5 ka, lake levels again dropped rapidly (as discussed later) and have remained at intermediate to low levels since.

A river's flood- and low-stage levels are useful indicators of local climatic conditions. The Nile River has received a lot of attention, resulting in a significant body of literature about its paleohydrological conditions. An approximate precipitation history has been reconstructed from its water levels (**Figure 6**). At present, the Nile River receives a significant component of its discharge from headwaters in the highlands of Ethiopia. Rainfall in this region is currently dominated by the African–Indian monsoon system. From 20–12.5 ka, the Nile River was braided and highly seasonal, indicating drier conditions (Kutzbach 1987), consistent with the other paleoclimate records from the surrounding region. Between 12 and 5 ka, high water marks in Egypt indicate stronger North African monsoons for the period, followed by potential weakening starting around 4 ka.

Two paleohydrological proxy records from the high altitude tropics of Central Asia (38° N), recording, total particles, sulfate fluxes, δ^{18}O proxies of Dunde ice cores (5.3 km above sea level),

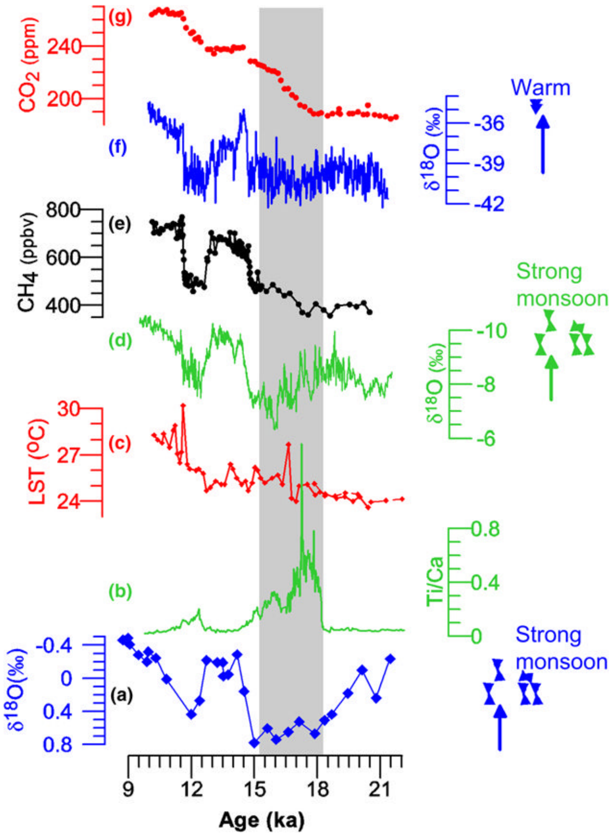

Figure 4 Paleoclimatic proxy records of the last deglaciation. (a) Seawater oxygen isotopes derived from paired Mg/Ca and δ^{18}O measurement of the surface living foraminifera *Globigerinoides ruber* (Rashid et al. 2011); (b) Ti/Ca ratios in bulk sediment from western equatorial Atlantic, interpreted as a proxy for high Amazon River runoff (Jaeschke et al. 2007); (c) TEX$_{86}$-derived surface temperature of Lake Tanganyika; (d) δ^{18}O in Shanbao speleothems (Wang et al. 2005); (e) atmospheric methane concentration (Chappellaz et al. 1997); (f) Greenland Ice Sheet Project 2 (GISP2) methane and oxygen isotope ratios (δ^{18}O) (Blunier and Brook 2001); and (g) atmospheric CO$_2$ from Antarctic Dome C (Monnin et al. 2001) placed on the GISP2 timescale. All records are plotted according to their independent age models.

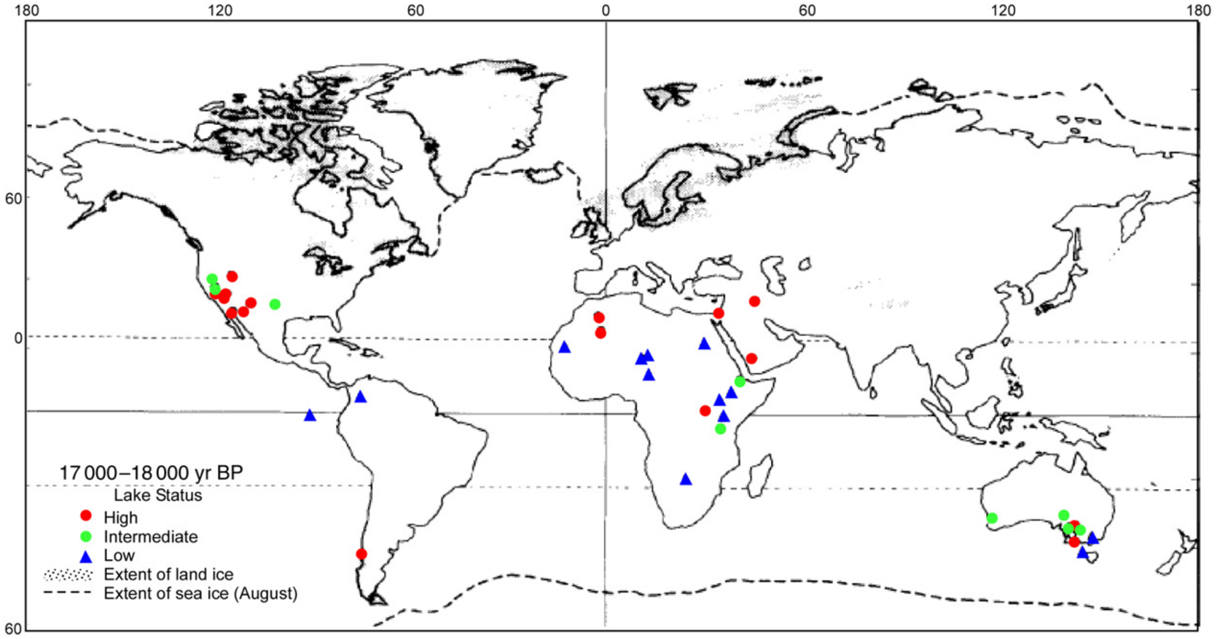

Figure 5 Lake level status during the LGM. Modified after Street, F. A. and A. T. Grove, 1979: Global maps of lake-level fluctuations since 30 000 yr. *B. P. Quat. Res.* **12**, 83–118; Gasse, F., 2000: Hydrological changes in the African tropics since the Last Glacial Maximum. *Quat. Sci. Rev.* **19**, 189–211.

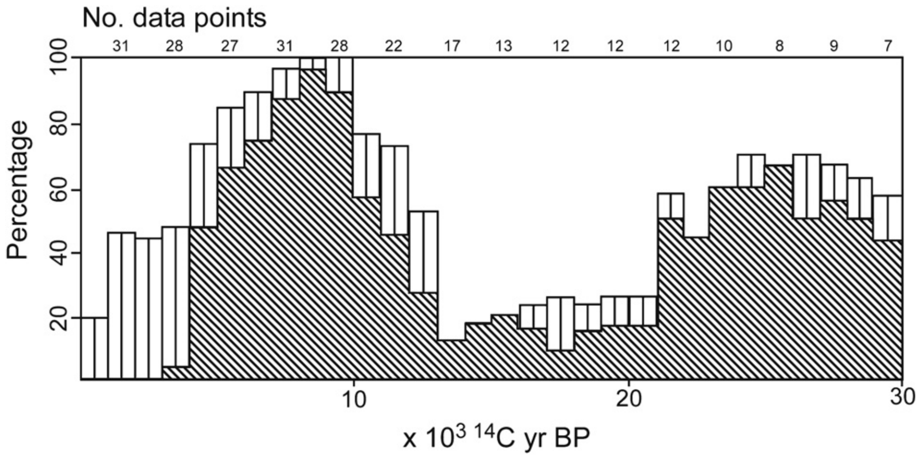

Figure 6 Lake level status for the intertropical African region during the past 30 ka. Street, F. A. and A. T. Grove, 1979: Global maps of lake-level fluctuations since 30,000 yr. *B. P. Quat. Res.* **12**, 83–118; Gasse, F., 2000: Hydrological changes in the African tropics since the Last Glacial Maximum. *Quat. Sci. Rev.* **19**, 189–211.

and lake levels of Africa indicate significant changes in the climate (Figure 7). It is noteworthy that the increased intensity of the African–Indian monsoon (high lake levels) during the early Holocene (11–8 ka) is positively correlated to less dusty and windy climate of the Qaidam Basin of northcentral China (Figure 7). The accumulation rate of ice, as inferred from the sulfate aerosol flux in the Dunde ice cap just northeast of the Qaidam Basin (Figure 7), also shows an inverse relationship between the South Asian and African monsoon records between 10 ka and present (Thompson et al. 1989). Low sulfate concentrations are correlated with high water stands, as this would in effect reduce the area of exposed desiccated sulfate-rich beds in the Qaidam Basin. δ^{18}O and particulate flux records from the same ice core show that the regional climate preceding the Holocene transition (before 12 ka) was colder and windier than it is at present. It is noteworthy that the pattern of low African lake levels between 14 and 21 ^{14}C-kyr are tied to high-altitude but low latitude dry and windy climate as inferred from high dust, low sulfate and more negative δ^{18}O values extracted from the Dunde ice-cap (Figure 7). These records suggest that a sharper (than modern) temperature gradient and ice boundary conditions were present during the LGM, which strengthened and pushed the polar front further south, leading to increased frontal precipitation in the midlatitudes, despite the colder temperatures. However, the anticorrelation between the Dunde ice core records (which seems to suggest a dry and windy climate over the Qaidam Basin) and high African lake level (inferring a wetter and humid climate between 22 and 30 ^{14}C-ky) is not clearly understood. One of the possibilities could be a mismatch between the age models where the former records need to be retuned. Another possibility

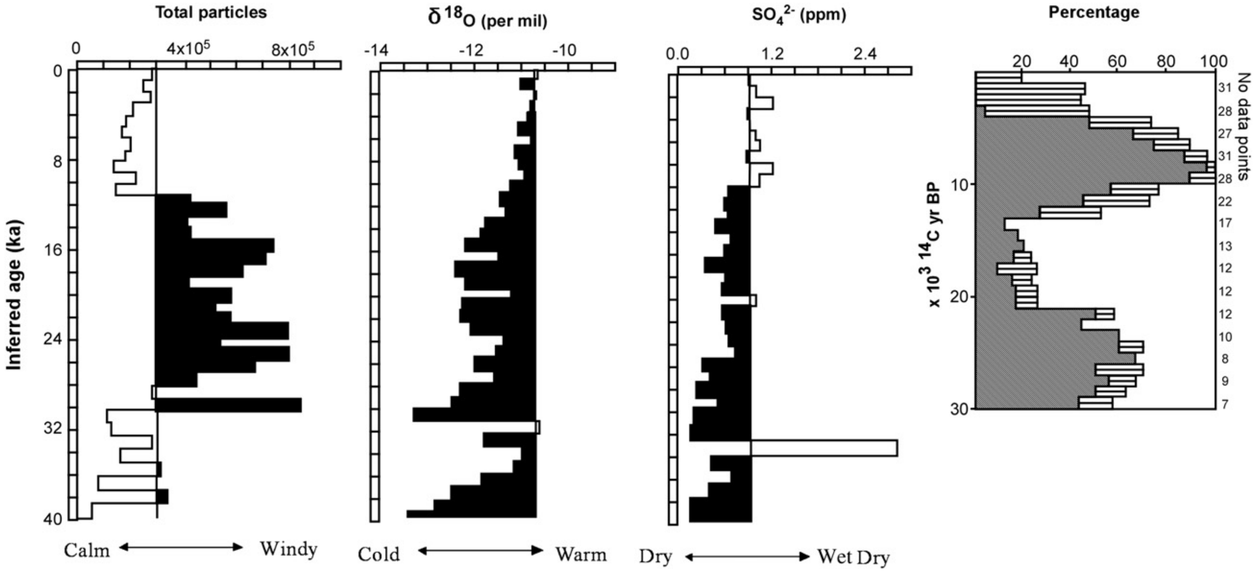

Figure 7 Downcore plots of total particles flux, δ^{18}O, and sulfate flux (parts per million) from the Dunde ice cap (Thompson et al. 1989) and African lake levels (Street and Grove 1979). Reproduced from Thompson, L. G., et al. 1989: Holocene Late Pleistocene climatic ice core records from Qinghai-Tibetan Plateau. *Science*, 246, 474–477.

is that the geographic configuration of the Qinghai-Tibetan ice sheet was different between 22 and 30 ^{14}C-ky in comparison to the LGM, hence influencing the regional climate of the Qaidam Basin. The latter possibility needs to be tested through modeling studies.

5.08.4.2 Marine Sediment Records

A large body of paleoclimatic records is available from the Somali margin of the western Arabian Sea and Arabian Sea in general, as discussed earlier. Here, the correlation of the eastern African climate with that of the Arabian Sea is discussed. Because the southwest winds of the ISM commonly pass over East Africa before turning eastward across the Arabian Sea, various pollen species characteristic of their climate regime are incorporated into the ocean bottom sediments. The percentage of pollen from distant source regions is also a proxy for the strength of the monsoon winds across this region, and most likely over the west coast of India. During the LGM, the pollen data show moderate–high values of steppe and Sahelian species and low humid tropical counts (van Campo et al. 1982). Between 12.5 ka and the climatic optimum (around 8 ka), as the humid tropical species increased toward their highest percentages, a short-term reversal of the trend exists corresponding to 11–10 ka, reflecting a brief period of a cold and dry climate. This latter event is now commonly known as the Younger Dryas (**Figure 3**), which has been reported from many tropical paleoarchives (Thompson 2011). From this point, both the Sudanese savanna and the African montane pollen show steady increases until 8 ka, indicating increased moisture and intensified long-distance transport, respectively.

Several processes related to monsoon strength in the African–Indian region create proxy signals in ocean sediment cores (Clemens et al. 1991; Gupta et al. 2005). Upwelling of cold and nutrient-rich waters (almost equal to high productivity) along the western Arabian Sea is induced by strong southwest monsoon winds. Strong winds also aid aeolian transport of lithogenic sediment from the Arabian Desert to the Arabian Sea. For example, deposition of 70% of the biological and 80% of the lithogenic sediments in the northwest Arabian Sea occurs during summer monsoons. Therefore, sediment cores can preserve monsoon signals (both the strength and timing). In addition, sea-surface temperature (SST) estimates from sediment cores (via foraminiferal census) in the southern subtropical Indian Ocean can be used as a proxy for latent heat availability (as cross-equatorial moisture transport provides 70% of latent heat for summer monsoons; Webster et al. 1998) to the Qinghai-Tibetan Plateau. SST values are anticorrelated with strong summer monsoons since high evaporation rates transferring latent heat to the atmosphere act to cool sea-surface waters (Bard et al. 1997).

5.08.5 Holocene Climate

It has been a common and prevailing view, based mostly on the Greenland ice-core δ^{18}O records, that the Holocene was rather uniform and remarkably stable in comparison to the preceding stadial and interstadial climate (MIS 2–3). However, it appears that the tropical Holocene climate variability may have been greater than has been assumed as more tropical paleoclimatic records emerge from high-elevation ice cores (Thompson 2011), lake sediments (Gasse 2000), cave deposits (Wang et al. 2005), and marine sediment records (Rashid et al. 2011; and references therein). One of the most striking illustrations of such climate variability is the drying of most of the North African lakes. This drying is commonly dubbed the demise of the African Humid Period (AHP) (de Menocal 2001; Adkins et al. 2006), a time when most of the North African region was dotted with numerous lakes, which have since dried out partially or completely disappeared. The transition from a wetter AHP to dry and desert conditions occurred between 6 and 5 ka (depending on the longitude). It is not possible to provide an exhaustive list of all the lake records and their paleoclimate history (Gasse 2000); however, a few lake records have been plotted with other proxy records of climate in **Figures 8 and 9**.

Although precise chronology of these lake records are rare because of lack of dating materials, changes in water levels of four tropical and North African lakes are shown in **Figure 8** for the Holocene. A general trend toward high lake level appears between 10 and 5 ka and then drops to present low lake levels. The high lake levels were punctuated by three short-duration dry events at 12, 8.4, and 6.8 ka, which may correlate to the

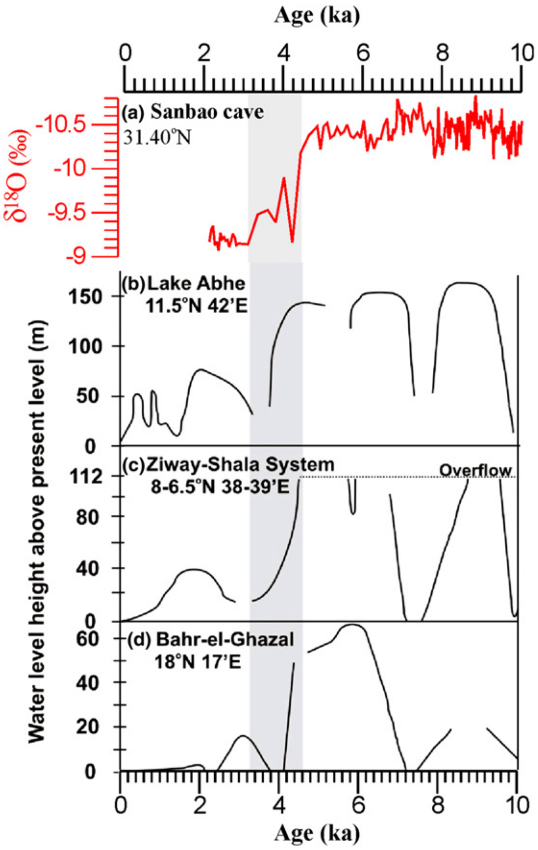

Figure 8 Oxygen isotopes (δ^{18}O) from Shanbao speleothems in northeastern China (Wang et al. 2008) (a) and lake levels from Lakes Abhé of Ethiopia-Djibouti (b), Ziway-Shala of the main Ethiopian Rift (c), and Bahr-el-Ghazal of western South Sudan (d) (Street and Grove 1979; Gasse 2000) are plotted versus age (ka). Note the vertical gray bar highlights the wet to dry climate transition.

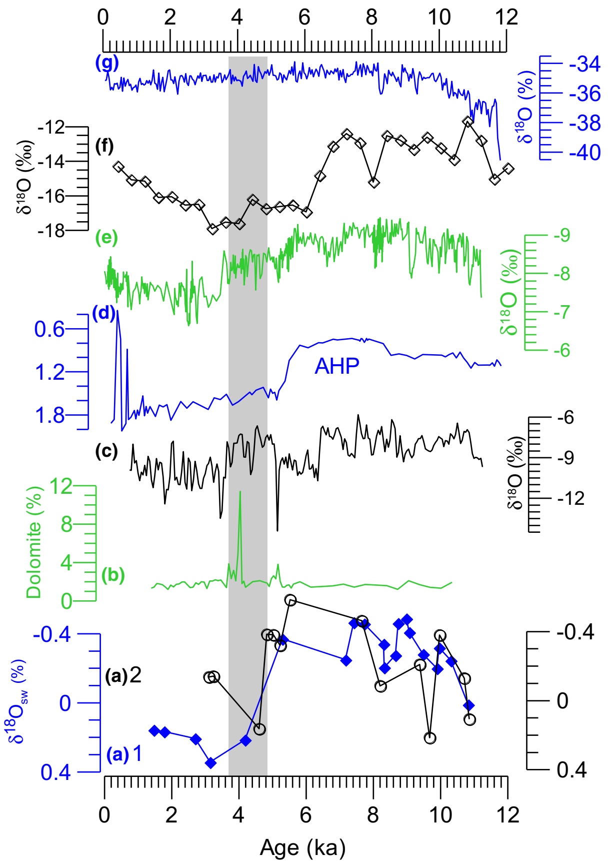

Figure 9 Holocene climate records from the greater Asian region are plotted in comparison with Greenland, Tibetan, and Kilimanjaro ice-core data according to their independent age models. (a1–a2) Andaman Sea (Rashid et al. 2007) and Bay of Bengal seawater $\delta^{18}O$ values (Rashid et al. 2011); (b) Gulf of Oman dolomite concentration (Cullen et al. 2000); (c) Kilimanjaro ice core (NIF3) $\delta^{18}O_{ice}$ (Thompson 2011); (d) African dust flux (de Menocal 2001); (e) $\delta^{18}O$ records from Chinese (Dongge) cave (Wang et al. 2005), (f) Tibetan (Guliya) ice core, and (g) Greenland ice cores. The gray bar shows the major climate transition between 5 and 4 ka. Note: *Y*-axis representing African dust flux (d) is reversed. AHP: African Humid Period.

North Atlantic ice-rafting events of the Holocene (Bond et al. 2001). In addition, there are also fluctuations in the water level of Lake Abhé of Ethiopia-Djibouti (at 11.5° N; Gasse 1977), which rose to a maximum of 150 m, whereas Lake Bosumtwi of Ghana (6.30° N; Talbot et al. 1984) overflowed above 50 m. This difference in lake levels may be due to the amount of rainfall or the constriction imposed by the physiographic framework (smaller versus larger lake size). High water marks of the Nile River in Egypt suggest stronger monsoon for the same period as well, followed by potentially much weaker monsoon starting around 4 ka. The presence of sapropels (black, organic-rich muds) in the Mediterranean Sea corresponding to this period (12–8 ka) are the likely result of large freshwater pulses from the monsoon-fed Nile River (Figure 8). In addition to the lake levels, increases in freshwater discharge have also been identified for the Niger and Senegal Rivers for the early Holocene period (Weldeab et al. 2007), which are consistent with wetter tropics during the early Holocene.

During the late Holocene (5 ka to present), a reduction in rainfall and dry climate conditions is demonstrated in the tropics by dry lake beds or low lake levels and desert conditions spanning a significant portion of West Africa to northeast China (Gasse 2000). The two most dominant climate events, namely, the 5.2- and 4.2-ka events, are nested within this period and are often discussed in the context of demise or abandonment of civilizations. The 5.2-ka event is preserved in diverse paleoclimate archives that include ice-core oxygen isotope records from Mount Kilimanjaro and Huascarán in northern Peru (Thompson 2011), methane records from Antarctica and Greenland (Chappellaz et al. 1997; Blunier and Brook 2001), marine sediment records from the Bay of Bengal (Rashid et al. 2011), and deposition of Saharan dust in the South American Andes (Thompson 2011). Other ice-core proxies, including dust and soluble chemical species such as Cl^- and SO_4^{2-}, also show drastic increases associated with the 5.2-ka event (Thompson 2011).

Terrestrial records, such as trees preserved in a standing position hundreds of feet below the surface of Lake Tahoe (Lindstrom 1990), suggest a wetter climate in the southwest region of the United States. Emerging plants from the retreating margins of an Andean glacier (Thompson 2011) and the 'Tyrolean ice man' or 'Özti' (Baroni and Orombelli 1996) in the eastern Alps are other notable observations concomitant with the 5.2-ka event.

The most widely recognized and widespread abrupt climate event of the late Holocene is dated between 4.5 and 4 ka and is found in many tropical and extratropical paleoclimate archives. It is associated with prominent dust peaks in the tropical ice cores, low lake levels (Dalfes et al. 1997; Gasse 2000) (Figure 9), and weakening of the Indian and Asian monsoons, and is interpreted as a major dry interval during the late Holocene. Marine sediment records from the Gulf of Oman (Kerr 1998; Cullen et al. 2000) and Bay of Bengal (Rashid et al. 2011), as well as lake records from the Gharwal Himalayas and northern Africa, also indicate dry climatic conditions around 4.2 ka. These events are also expressed in archeological data from the Euphrates and Tigris drainage basins. Similar to the 5.2-ka event, it is also believed to have lasted at least a few centuries. This event was related to profound changes in the hydrological cycle in the tropics and midlatitudes and appears to correlate with the decline of past civilizations (Weiss et al. 1993; Rashid et al. 2011).

5.08.6 Past Civilizations and Tropical Hydrological Cycle

Modern tropical hydrological processes influence the distribution of water resources and present-day population density distributions. It is not difficult to see how tropical paleohydrology would have constrained past civilizations that lacked the technical capacity of modern society. At present, nearly 55% of the world's population is found in areas of the globe that receive the highest amounts of rainfall. Almost one-quarter of humanity lives in the Ganga–Brahmaputra–Meghna and Yangtze/Yellow River valleys alone and are directly affected by the twin influences of the Indian–Asian monsoon and the great rivers flowing from the Qinghai-Tibetan Plateau and southern Himalayas. No other region of the world has such a close relationship between humankind and the hydrological cycle than the tropics. Climate studies have shown that the strength of the Indian–Asian monsoon has varied over many timescales, driven by different processes ranging from the gradual uplift of the Qinghai-Tibetan Plateau to the annual cyclicity of ENSO (Clift and Plumb 2008). As the monsoon has varied through time, it has also impacted the lives of people who depend on regular and adequate rains for agriculture. It is therefore not surprising that the onset of drying periods between 4.5 and 4 ka (**Figure 9**) (discussed earlier) coincides with the abrupt end of many civilizations, including the Fourth Dynasty in Egypt (Dalfes et al. 1997). The decline was not limited to tropical Africa but extends to the Harappan civilizations of the Indus River valley (northwest India; Rashid et al. 2011), the Akkadian Empire (Persian Gulf; Kerr 1998) and northeast Chinese civilizations (Rapp and Jing 2011).

An earlier Vedic civilization, which flourished along the banks of the Sarasvati River, has also recently been identified based on fossils of elephants and bamboo curtains (Paliwal 2011). Quaternary gypsum deposits of Rajasthan suggest the existence of an advanced civilization earlier than 12.8 ka, making this civilization older than the Harappan and Mohenjo-Daro civilizations (5 ka) of the Indus Valley (Weiss et al. 1993; Rashid et al. 2011) and northeast China (Rapp and Jing 2011). Abrupt climate events during the Holocene, recorded in a series of lake records and groundwater data from the western Indian peninsula in combination with neotectonic activity, altered the drainage pattern that caused a disappearance of the Vedic Sarasvati River and other tributaries of the Indus River and may have led to the demise of this civilization as well. However, lack of high-resolution radiocarbon dates prevents correlation of these terrestrial records to ISM records (Rashid et al. 2011), which is essential to evaluate the impact of climate change on the fate of ancient civilizations. The second period of drought at 3.2 ka lends support for the hypothesized hydrological link between tropical areas in southeast Asia and North Africa and the resulting effects on civilizations through tropical rainfall.

5.08.7 Concluding Remarks

1. A large number of paleoclimate records show that the tropical hydrological cycle was strengthened and weakened in tandem with the D/O warming and cooling cycles as recorded in the oxygen isotopic ratios of Greenland ice cores. The weakening and strengthening of the hydrological cycles were tied to the shift in the mean position of the intertropical convergence zone to a more southern latitude than its position under the modern climate configuration.
2. The LGM (18–24 ka) is characterized in all of the tropical records as a period of generally dry and windy climate. A majority of paleolake level data from Africa, marine sediment records from the Arabian Sea and Bay of Bengal, and South Asian speleothem oxygen isotopic data suggest that the African–Indian–Asian monsoons were weaker during this time. As a result, biological activity off the coast of Oman margin was weaker and the outflow from the Indian subcontinent rivers was low compared to modern outflow. Orographic influence of the greatest polar ice sheets coupled with a potentially larger Tibetan Plateau ice sheet, larger sea-ice extent in the North Atlantic Ocean, and perennial Eurasian snow cover likely played a wider role in limiting the inland propagation of the Indian–Asian monsoon. This altered configuration deprived the North African region from adequate rainfall, resulting in the drying of numerous lakes.
3. The early Holocene climatic optimum period (ranging from 10.5 to 6 ka) is recoded in varying degrees and durations, but is present in virtually all records, indicating overflow of many African lakes, stronger Indian–Asian monsoon, and associated higher rainfall. A northward migration of the mean position of ITCZ is the most plausible explanation for the lag in maximum lake level stands recorded at the most northerly tropical regions. There exists a significant amount of evidence to support widespread drought conditions beginning about 4.5 ka, with only moderate recovery to present. In addition, as evidenced by the desiccation of lakes in northwest India and parts of North Africa, the northernmost extent of monsoon rains retreated and has not since returned to this region.
4. The onset of a late Holocene drought period coincides with the demise of many ancient civilizations surrounding the North African region, northwest India, and northeast China. It is beyond the scope of this chapter to describe the archeological evidence that seems to negate connections between the demise of past civilizations and changes in the amount of rainfall. However, the authors suggest a tentative link between the two, which might provide fodder for further research. During the late Holocene, there were likely several hundred million people on the planet with only a fraction subjected to this acute hydrological condition. The impact of such a rapid and sustained drought event today with 7 billion people would be devastating and thus requires attention.

In the last three decades, we have witnessed many events that underscore an inherent risk that humans face today should a similar drought event were to occur. It is therefore urgent that society develops a much better understanding of what caused these events, their consequences, and, potentially increase their predictability (Rial et al. 2004). It is clear that the paleoclimate community has uncovered information about Earth's natural climate behavior that is unprecedented in the instrumental record and is not well appreciated by the broader climate science community. Given the growing concern that Earth may be experiencing another abrupt climate change today, these past episodes of abrupt climate change provide us an opportunity to study how the climate system enters an abrupt change by developing the necessary data that can be coupled with model experiments designed to answer why Earth has experienced such dramatic changes in the recent past. This will shed light to adopt a bottom–up climate vulnerability approach.

5. In the modern climate setting, rain does not fall uniformly across the globe, especially in the tropical regions. The locus of maximum rainfall is located over the monsoon region in Asia where convergence of hemispheric winds is absent,

making the ITCZ a secondary factor. Even in other regions showing strong links to the seasonal migration of the ITCZ, the range of migration is not uniform. In spite of these variations, modern climate is known to have a global Walker Circulation capable of coordinating tropical hydrology. The coherence in paleoclimate records suggests that such circulations may have been present during the periods discussed here.

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5.09 The Potential of Precipitation Remote Sensing for Water Resources Vulnerability Assessment in Arid Southwestern United States

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5.09.1 Introduction

Arid and semiarid regions constitute approximately 25% of the contiguous United States and a significant fraction of the world. Understanding and management of water resources entail reliable and timely data sets, analytical tools, and representative models. In arid and semiarid regions, available water resources are often very sensitive to seasonal to interdecadal climate variability. Therefore, reliable quantitative estimates of the components of the hydrologic cycle are fundamental to water resources management and risk assessment. In particular, precipitation is one of the key variables that plays a significant role in the hydrologic cycle.

Accounting for climate variability and population growth is fundamental to vulnerability assessment of water resources system. For example, studies have highlighted that water resources and flood risks are sensitive to climate change and thus, watershed management and planning strategies should be adjusted accordingly (Stoll et al. 2011; Sivakumar 2011, among others). These sensitivities are particularly high in the western United States (Reclamation 2011; Seager et al. 2007; Schlenker et al. 2007; Cayan et al. 2008).

Western United States can expect multiyear periods of drought followed by unusually wet winters along the West Coast (often in phase with the El Nino Southern Oscillation), shifts in the timing of wet and dry periods, and increases in summer monsoonal moisture. On the other hand, population of Arizona, Southern California, and Southern Nevada are projected to increase in a 30-year period (1990–2020) by 90, 57, and 104%, respectively (Morrison et al. 1996). This stands to not only increase in water stress in southwestern United States, but height flood risks through land cover changes associated with expanding urban areas.

In recent years, Intergovernmental Panel on Climate Change (IPCC) reports (e.g., IPCC 2007) attempted to assess potential climate change and variability impacts on the water cycle and precipitation, among other variables. While IPCC reports provide valuable information to the climate community, the resolution is too coarse for engineering and decision-making applications, which require high resolution and local information (Pielke et al. 2011; Solomon et al. 2007).

Improving our understanding of the water cycle, along with the development of reliable high-resolution precipitation data sets, is essential for monitoring and predicting water resources. Currently, rain gauge measurements and radar data provide the main inputs for water resources management and hydrologic forecasting (e.g., streamflow simulation, flash flood warnings, drought monitoring, and weather watches) across the United States. Poor spatial sampling and uneven distribution are the main limitations of rain gauges. Obviously, these limitations often make the data inadequate to support water resources studies, particularly over large scales. Given the high variability of precipitation in space and time (Corradini and Singh 1985; Troutman 1983), most parts of the globe lack sufficient number of rain gauges to capture precipitation accurately.

Weather radar systems provide valuable and detailed information on precipitation. However, in most parts of the globe, radar networks are not available. Even in the United States, which is equipped with state-of-the-art radar systems, there are regions with extensive topographic relief that suffer from poor radar coverage (e.g., western United States; Maddox et al. 2002). For example, Maddox et al. 2002 demonstrated that in the western United States, at 1000 m above ground level, the radar coverage area is substantially less than 3000 m above ground level (Figure 1).

Evidently, lack or absence of in-site and radar installations hamper the development and use of water resources management and decision-making model. Therefore, alternative methods of precipitation estimation with sufficient sampling density and reliability are necessary for operational applications.

Satellite-based precipitation data sets have the potential to improve precipitation observation at a quasi-global to even global scale. In the past three decades, the National Aeronautics and Space Administration (NASA), National Oceanic and Atmospheric Administration (NOAA), and many other international agencies have sponsored satellite missions to improve precipitation estimation. Thus far, many algorithms have been developed to retrieve precipitation in near real-time (e.g., Tropical Rainfall Measuring Mission (TRMM) 3B42, Huffman et al. 2007; CPC Morphing Technique (CMORPH), Joyce et al. 2004; and Precipitation Estimation from Remotely Sensed Information using Artificial Neural Networks (PERSIANN), Sorooshian et al. 2000, Hsu et al. 1997).

It is well known that satellite-retrieved data sets have several advantages over rain gauge measurements (e.g., higher spatial

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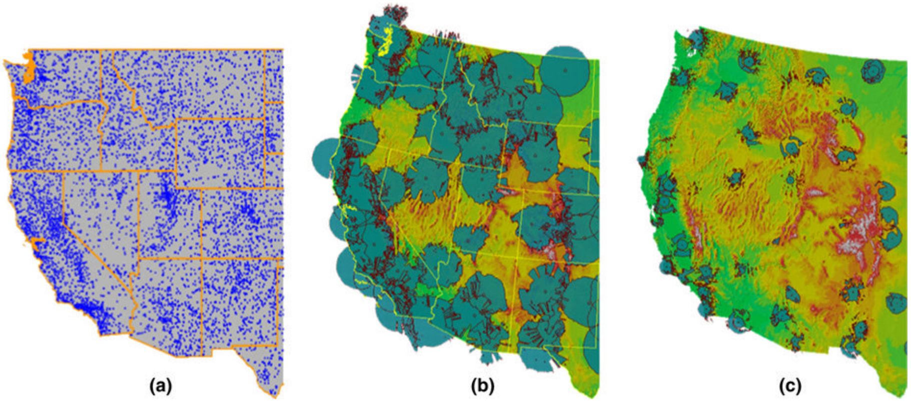


Figure 1 (a) Rain gauges (NCDC data); (b) radar coverage 3000 m above the ground level; (c) radar coverage 1000 m above ground level. After Maddox, R., J. Zhang, J. Gourley, and K. Howard, 2002: Weather radar coverage over the contiguous United States. *Weather Forecast.*, **17**, 927–934.

resolution and uninterrupted measurement). However, satellite precipitation products have not yet fully integrated into water resources engineering and management models, mainly because of (1) the relatively short length of the data record for climatological studies, (2) retrieval errors due to the indirect nature of satellite observations, (3) the undetermined uncertainties and error bounds, and (4) a general lack of experience in the utilization of satellite data for practical applications. In the following, after a brief discussion on remote sensing of precipitation, the potential applications of satellite-based data to drought monitoring, flood forecasting, and water resources management are highlighted. It is hoped that this introduction motivates greater utilization of satellite data in water resources management and decision making.

5.09.2 Remote Sensing of Precipitation

Since the launch of the Television and Infrared Observation Satellite (TIROS-1), the first meteorological instrument, the number of remotely sensed observations has been increasing. Satellites can be categorized into two main groups: (1) low earth orbit (LEO, revisiting the same spot on the Earth at regular intervals) and (2) geostationary (GEO, hovering over the same location on Earth continuously, Kidd 2001).

GEO satellites are placed at altitudes of 35 880 km and move at the speed of the Earth's rotation. GEO satellites are widely used to measure meteorological variables using the visible (VIS) and infrared (IR) wavebands (Levizzani 2008). On the other hand, LEO satellites are positioned in sun-synchronous orbits and thus are able to visit any spot on the Earth at regular intervals. Thus far, passive microwave (PMW) sensors have been installed on LEO satellites. These sensors offer more accurate precipitation estimates than the GEO satellites (Huffman et al. 2007; Hsu et al. 1999). On the other hand, GEO satellites provide more frequent measures of precipitation over the hemispherical disk, which is crucial for hydrologic prediction and real-time monitoring systems.

IR and VIS scans provide frequent (less than 30 min) estimates of cloud-top temperature and albedo that can be used to retrieve precipitation estimates. It is noted that the indirect nature of precipitation estimation from sensors on GEO platforms constitutes considerable uncertainty in precipitation estimates. On the other hand, the PMW sensors aboard LEO satellites offer more direct, and thus more accurate, instantaneous precipitation data. However, LEO satellites visit each spot on Earth only once or twice per day, which may not be sufficient to capture temporal variability of precipitation. The low temporal resolution of LEO satellites can be compensated for by integration of data from GEO sensors in order to obtain better temporal and spatial sampling of diurnal rainfall variability. Verification and validation studies indicate that merging LEO and GEO satellites data exploit the advantages of both types of sensors in precipitation estimation (Xie and Arkin 1997; Turk et al. 2006; Adler et al. 2001; Huffman et al. 1997; Levizzani et al. 2007).

As mentioned earlier, different satellite rainfall-retrieval algorithms have been developed to derive precipitation rates in near real-time (e.g., TRMM Multi-Satellite Precipitation Analysis (TMPA), CMORPH, PERSIANN). A comprehensive review of precipitation algorithms is beyond the scope of this chapter. For reviews and product comparisons, the interested reader is referred to Tian et al. (2009), Adler et al. (2001), Levizzani and Amorati (2002), Tian et al. (2007), and Kidd (2001). In the following, the PERSIANN retrieval algorithm is discussed in more detail. This algorithm uses an artificial neural network (ANN) classification approach to estimate precipitation rates. The original version of the PERSIANN algorithm was based on IR imagery from GEO sensors, while the current operational version is extended to include PMW data from LEO satellites for parameter adjustment and calibration.

The PERSIANN retrieval scheme transforms IR images to precipitation estimates in three steps: (1) extracts the mean and variance of cloud-top brightness temperatures in the vicinity of each pixel; (2) classifies the extracted features (e.g., cloud-top temperature patterns); (3) translates the classified features to precipitation rates. The current operational version of the PERSIANN runs in two parallel modes: (1) 'simulation mode,' which produces precipitation rates at the 0.25° × 0.25° gridded resolution and every 30 min based on the GEO IR data and (2) the 'continuous update mode,' which continuously updates the parameters of the algorithm using PMW-based precipitation data (Hsu et al. 1997). PMW calibration is performed by dividing the PERSIANN coverage overlapping subregions. The

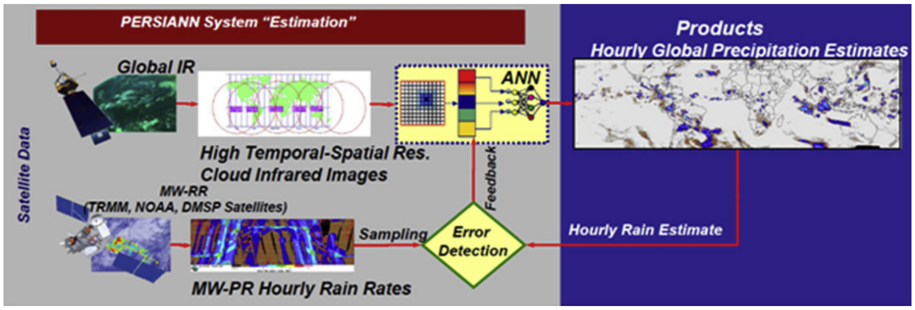


Figure 2 Components of the PERSIANN precipitation algorithm; MW, microwave; PR, precipitation radar. Modified after Hsu, K., H. Moradkhani, and S. Sorooshian, 2009: A sequential Bayesian approach for hydrologic model selection and prediction. *Water Resour. Res.*, **45**, 2038–2059, w00B12. Reproduced from Hsu, K., and S. Sorooshian, 2008: Satellite-based precipitation measurement using persiann system. *Hydrological Modeling and The Water Cycle – Coupling the Atmospheric and Hydrologic Models*, S. Sorooshian, E. Coppola, B. Tomassetti, M. Verdecchia, K. Hsu and G. Visconti, Eds., Springer, 27–48.

simulation mode estimates are then adjusted and calibrated using the instantaneous PMW data that fall within the same subregion. The interested reader is referred to Hsu et al. (1997) for a more detailed discussion on the calibration procedure.

In the simulation mode, the PERSIANN algorithm relies on gridded IR images from multiple satellites such as the East and West Geostationary Operational Environmental Satellites (GOES) and the Geostationary Meteorological Satellite (GMS-5) provided by the NOAA Climate Prediction Center (CPC, see Janowiak et al. (2001) for details). The required PMW-based precipitation data are obtained from the available LEO satellites. It is worth pointing out that GEO data can be obtained at up to 15 min intervals; however, PMW estimates are not available at such a high time resolutions for parameter calibration.

Currently, PERSIANN precipitation estimates cover 60° S to 60° N, with a time interval of 3 h and a spatial resolution of 0.25° since 2000. PERSIANN estimates are then accumulated to various temporal resolutions (e.g., daily) for hydrologic applications. Figure 2 displays the components of the retrieval algorithm.

5.09.3 Application to Water Resources Vulnerability Assessment

5.09.3.1 Drought Monitoring

Droughts are relatively common in arid and semiarid regions. Sensitivity of agriculture and many other industries to drought conditions is well recognized. Therefore, drought monitoring and prediction is of particular importance over arid and semiarid regions. In recent years, satellite data sets are being used for drought analysis. The African Drought Monitor (Sheffield et al. 2006), for example, produces land-surface hydrological conditions. In this model, PERSIANN and TMPA data are used as input, while model outputs include drought conditions and quantitative estimates of water-budget components.

Anderson et al. (2008) investigated droughts based on vegetation response using TMPA precipitation data. The results indicated that higher water deficiencies coincided with critical months in the enhanced vegetation index (EVI). Anderson et al. 2008 concluded that satellite data can be used to investigate drought impacts on vegetation. Paridal et al. (2008) highlighted the potential of satellite precipitation estimates for drought monitoring in a case study across the Philippines. In a recent study, Zhang et al. (2008) demonstrated the application of remote sensing data to drought monitoring based on the plant water stress index (PWSI; Idso et al. 1981).

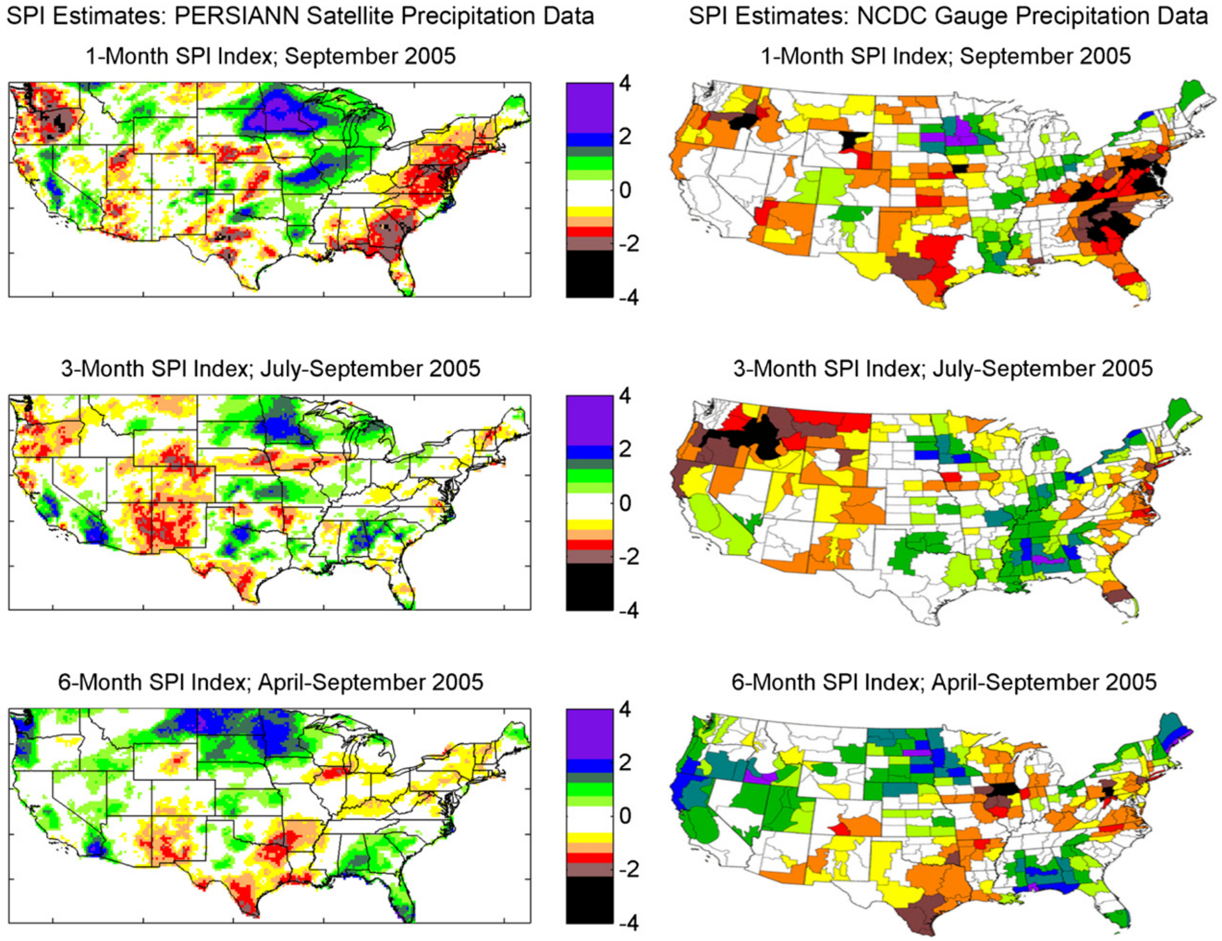
In the following, an example application of PERSIANN satellite data to drought analysis is demonstrated. The standardized precipitation index (SPI) is estimated for each precipitation pixel across the contiguous United States using real-time PERSIANN data and Global Precipitation Climatology Project (GPCP) data (Huffman et al. 1997). In this example, the log-term GPCP data are used to derive the climatology of precipitation, while real-time satellite data are used for drought monitoring. The SPI is employed to identify persistent lack of precipitation at various time scales (e.g., 3, 6, 12, and 24 months). In order to derive SPIs, a gamma distribution is fitted to the precipitation record, and the accumulated gamma distribution is then transferred to a normal cumulative density function (CDF). Consequently, SPI is standardized to a normal distribution having null mean and unit standard deviation (McKee et al. 1993). Table 1 lists the SPI classification of wet and dry conditions.

The SPI describes the amount of precipitation over a certain period in a normalized scale. A high SPI (>2.0) represents high precipitation accumulation, whereas a low SPI (<2.0) refers to precipitation less than the climatological mean over a certain period (e.g., 3-, 6-, and 12-month periods). The SPI indicates normal precipitation accumulation (near climatological mean). In other words, consecutive negative SPI values indicate persistent dry periods or drought conditions (McKee et al. 1993).

Figure 3 displays the SPI values derived using PERSIANN satellite data and GPCP climatology (left panels) and the

Table 1 SPI classification of wet and dry conditions

SPI index	*Climatic condition*
>2	Extremely wet
1.5–2.0	Very wet
1.0–1.5	Moderately wet
−1.0 to 1.0	Near normal
−1.0 to −1.5	Moderate drought
−1.5 to −2.0	Severe drought
<−2.0	Extreme drought


SPI Estimates: PERSIANN Satellite Precipitation Data

SPI Estimates: NCDC Gauge Precipitation Data

1-Month SPI Index; September 2005

3-Month SPI Index; July-September 2005

6-Month SPI Index; April-September 2005

Figure 3 SPI estimates using PERSIANN precipitation data (left panels) and the NCDC Global Historical Climatology Network (GHCN) data set (right panels).

National Climatic Data Center (NCDC) Global Historical Climatology Network (GHCN) gauge data set (right panels). In Figure 3, 1-month (Sep. 2005), 3-month (Jul.–Sep. 2005), and 6-month (Apr.–Sep. 2005) SPI values are presented in the upper, middle, and lower panels, respectively. Note that the NCDC drought analyses are at the climate division scale, as opposed to PERSIANN-based SPI values computed at the pixel scale. One can see that the patterns of wet and dry conditions are quite similar in both left and right panels. The differences between the SPI values are mainly due to the (1) normalization interval (NCDC employs long-term gauge data, while GPCP data are available from 1979) and (2) spatial scale (NCDC analysis are averaged over climate divisions, while satellite-derived SPIs are pixel based). Overall, Figure 3 demonstrates that satellite precipitation data can potentially be integrated into drought monitoring systems, particularly over remote areas where other sources of information may not be available.

For reliable drought analysis, long-term precipitation data sets are of primary importance. NASA's GPCP (Huffman et al. 1997; Adler et al. 2003) and NOAA's CPC Merged Analysis of Precipitation (CMAP, Xie and Arkin 1997) data sets have been providing precipitation data since 1979. On the other hand, the emergence of real-time high-resolution precipitation products provides a unique opportunity to integrate merged satellite data sets into drought monitoring and analysis systems. One of the limitations of the high-resolution satellite data is a relatively short length of record. Currently, long enough records can be obtained only by merging multiple products. Evidently, merging multiple products may lead to some level of inconsistency as products change over time.

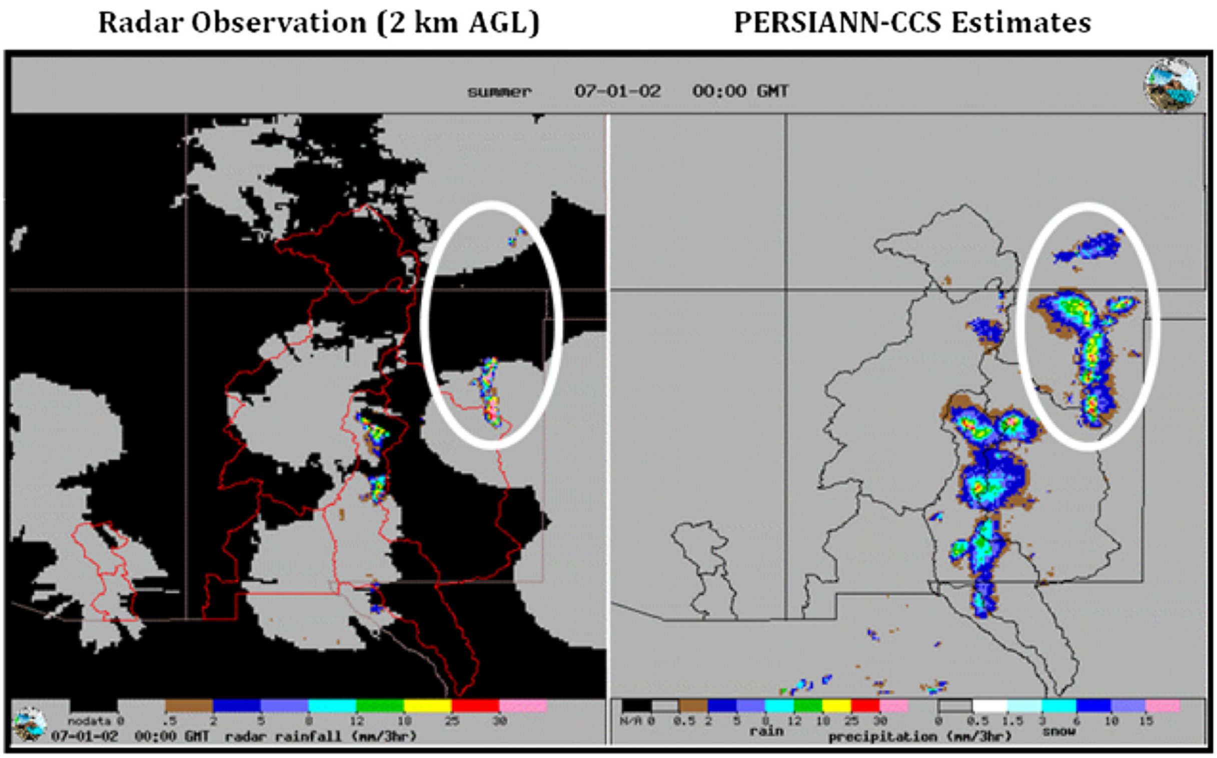
The community of satellite precipitation research continuously progresses toward better quality and higher space–time resolutions. In particular, efforts are underway to develop a consistent retrospective precipitation data set back to the early 1980s. Some of the high-resolution precipitation products (e.g., TMPA, CMORPH) rely mainly on more accurate but infrequent LEO data. This restricts their applicability for reconstruction of precipitation records for pre-PMW era (1997). On the contrary, the PERSIANN can be viewed as a two-phase algorithm: (1) the training phase, during which an ANN is trained based on PMW and ground-based observations and (2) the application phase, in which the trained model can be applied to IR-only images. Therefore, the PERSIANN algorithm is uniquely positioned to produce precipitation records prior to 1997 using historical IR observations. In the near future, this approach will provide a long-term high-resolution precipitation data set for weather and climate research and applications. This could bridge the gap between low-resolution long-term data and recent high-resolution precipitation data sets and the need for high-quality long-term data required for drought monitoring.

5.09.3.2 Flood Monitoring/Assessment

Floods are the most life-threatening hydrologic extremes and result in significant loss of lives and property damages. In fact, floods are one of the most common and widespread natural disasters. A 20-year (1985–2004) record shows that on average 150 flood events occurred each year across the globe. These events resulted in 7500 deaths and approximately $15 billion in property and economic damage (Stromberg 2007). The severity and impact of floods depend on several factors such as watershed characteristics, storm type and intensity, antecedent soil moisture, snowmelt, and land use change. Generally, any systematic approach to the simulation of streamflow has three main components: (1) model, (2) parameter estimation and model calibration, and (3) data requirements. It is our view that one of the major challenges in reliable hydrologic forecasting is providing accurate data sets as input to models. This section envisions future improvements that can be achieved by the integration of satellite data to streamflow simulation.

Among the required data sets, precipitation is perhaps the main driving force in streamflow simulation models (Cloke and Pappenberger 2009). Regardless of the choice of model, accurate measurement of extreme precipitation events is fundamental to flood forecasting. Traditionally, rain gauge observations have been the main input for streamflow simulations. However, unrepresentativeness of rain gauges across most of the world is a major limitation to support monitoring and predicting watershed response. As stressed earlier, radar networks are either not available or inadequate for operational applications, except in a few countries. Therefore, there exists the need to obtain alternative measures of precipitation to enable streamflow simulation and forecasting for operational applications.

Figure 4 highlights the importance of satellite data in flood forecasting applications. In the left panel, the gray areas show weather radar coverage in the southwestern United States, and the black areas represent no radar coverage, mainly because of terrain blockage. The right panel displays PERSIANN satellite precipitation estimates. As shown, in this particular event, radars did not detect a large part of the storm (black areas), while satellite estimates captured the entire event. Evidently, missing a large part of the storm would adversely affect the performance of flood forecasting models. In fact, even a sophisticated hydrological model cannot forecast flooding, if the input precipitation is not captured by ground-based observation networks.


Radar Observation (2 km AGL)

PERSIANN-CCS Estimates

summer 07-01-02 00:00 GMT
nodata 0 .5 2 5 8 12 18 25 30
07-01-02 00:00 GMT radar rainfall (mm/3hr)
N/A 0 0.5 2 5 8 12 18 25 30
rain
0 0.5 1.5 3 6 10 15
snow
precipitation (mm/3hr)

Figure 4 Importance of satellite data in flood forecasting applications. In the left panel, the gray areas show weather radar coverage in the southwestern United States. The right panel displays PERSIANN satellite precipitation estimates. As shown, radars did not detect a large part of the storm (black areas) mainly because of terrain blockage, while satellite estimates captured the entire event.

Flash floods, in particular, are very difficult to predict, as they occur in a relatively short time. Flash flood occurrence is affected by the amount of precipitation, antecedent soil moisture, soil type, and topography, among other meteorologic conditions. Among all, the amount of precipitation and its space–time variability are the main factors for reliable flash flood forecasting. Numerous studies have highlighted the significance of spatiotemporal variability of precipitation and its impacts on hydrologic applications (Corradini and Singh 1985; Schuurmans and Bierkens 2007; Fiener and Auerswald 2009; Haile et al. 2009; Fiener and Auerswald 2009).

In this regard, satellite precipitation data sets provide a great opportunity to capture the space–time variability of precipitation, particularly over regions where other means of precipitation measurement are sparse or nonexistent (Tang et al. 2009). However, lack of information on uncertainty of satellite data sets limits their application in operational flood forecasting (AghaKouchak et al. 2011). Despite extensive research, uncertainties of remotely sensed precipitation data have not yet been well quantified (Hossain and Huffman 2008; Margulis et al. 2006; Dong et al. 2005; Hossain and Anagnostou 2005; AghaKouchak et al. 2010a). Quantification and characterization of precipitation uncertainties are important as spatial and temporal variability in input precipitation is one of the main sources of error in rainfall–runoff processes and hydrologic predictions (Schuurmans and Bierkens 2007; Syed et al. 2003; Arnaud et al. 2002).

The quality of satellite data can be improved by merging different sources (multisensor) of data (e.g., gauge and radar) in order to obtain the optimal estimates of precipitation. Since each measurement technique or sensor has its own advantages and disadvantages, integrating multiple sensors may improve the quality of observations. In this regard, an adjusted version of the PERSIANN precipitation data (hereafter referred to as PERSIANN-MBA; monthly bias adjusted) are developed based on the GPCP version 2 (Adler et al. 2003). In this data set, the volumetric bias is removed based on monthly accumulations of the GPCP data. In other words, spatial patterns of precipitation are derived from original PERSIANN data, while the precipitation accumulations are adjusted by GPCP data.

Validation studies show that the PERSIANN-MBA is significantly improved with respect to the unadjusted rainfall estimates. This improvement is crucial for hydrological modeling. Figure 5 displays time series of observed precipitation and simulated streamflow over the Illinois River basin ((a) PERSIANN satellite precipitation data, (b) bias-adjusted satellite data (PERSIANN-MBA), (c) simulated streamflow using data in (a), and (d) simulated streamflow using data in (b)). In panels (a) and (b), the gray lines show the monthly averaged Stage IV radar reference data, whereas in (c) and (d) the gray

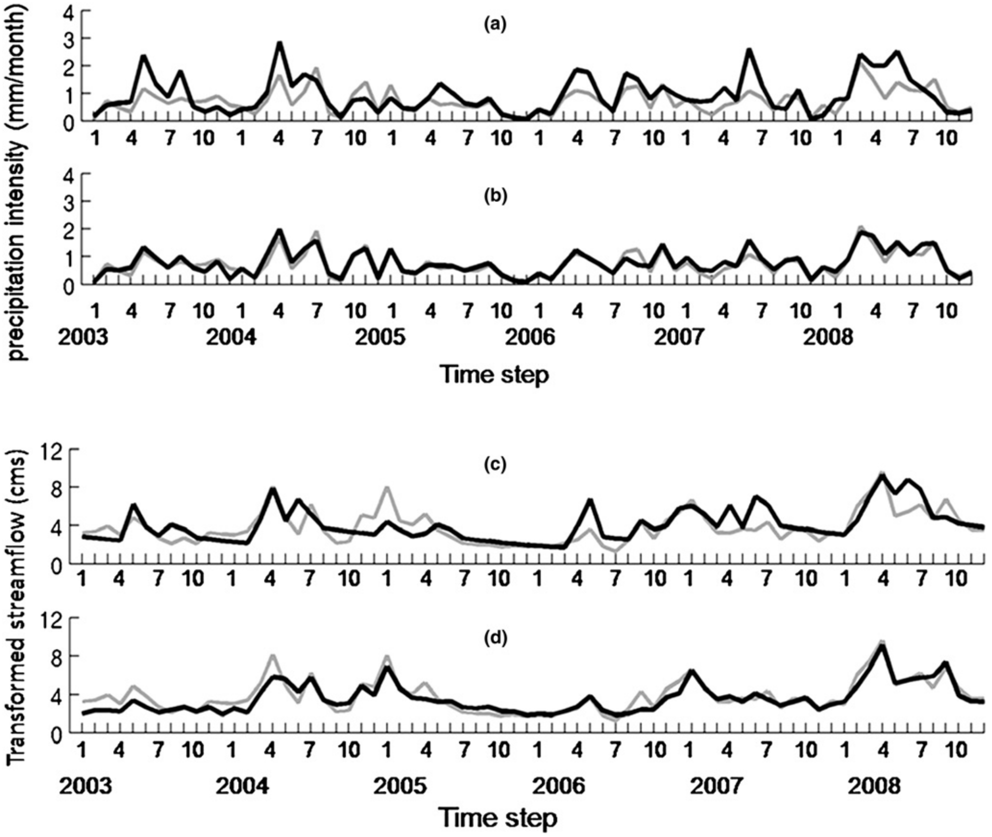


Figure 5 Time series of observed precipitation and simulated streamflow over the Illinois River basin. (a) PERSIANN satellite precipitation data; (b) bias-adjusted satellite data (PERSIANN-MBA); (c) simulated streamflow using data in (a); (d) simulated streamflow using data in (b). In panels (a) and (b), the gray lines show the monthly averaged multisensor radar reference data, whereas in (c) and (d) the gray lines represent monthly averaged observed streamflow (see Behrangi et al. (2011) for more details). Reproduced from Behrangi, A., B. Khakbaz, T. Jaw, A. AghaKouchak, K. Hsu, and S. Sorooshian, 2011: Hydrologic evaluation of satellite precipitation products at basin scale. *J. Hydrol.*, **397**, 225–237.

lines represent the monthly averaged observed streamflow. The simulated streamflows are derived using the Sacramento Soil Moisture Accounting Model (SAC-SMA) model as explained by Behrangi et al. (2011). Note that the simulated hydrographs (**Figure 5(c) and 5(d)**) are transformed using $Q_t = ((Q_s + 1)^{0.3} - 1)/0.3$ (Q_t, transformed runoff; Q_s, simulated runoff) for better visualization of peak flows (Hogue et al. 2000).

A visual comparison indicates that, while the original PERSIANN satellite data can capture the general precipitation patterns (**Figure 5(a)**), the PERSIANN-MBA version (**Figure 5(b)**) leads to a better agreement with reference measurements (gray lines). Note that the original PERSIANN precipitation data overestimate the precipitation intensity, particularly during the spring and summer months (**Figure 5(a)**). On the other hand, the PERSIANN-MBA data show significant improvement in estimating the seasonal variability and magnitude of the precipitation rate (**Figure 5(b)**). Consequently, simulated discharge derived from PERSIANN-MBA data exhibits better agreement with reference measurements (compare **Figure 5(c) and 5(d)**). It should be noted that GPCP and stage IV data sets are not purely independent, as rain gauges are used in both data sets.

Flood forecasting practice also relies on precipitation forecasts from the numerical weather prediction (NWP) models. NWP precipitation forecasts are processed as probabilistic estimates known as quantitative precipitation forecasts (QPF; Amburn 1992; Amburn and Wolf 1994). Obviously, the quality of forecasts will depend on the reliability of the precipitation estimates. However, NWP models may miss precipitation events, particularly small-scale and short-term systems. On the other hand, the initial conditions and variables are typically updated when observations become available. Without regular updating, the NWP model loses its skills in representing the precipitation amount and its space–time variability. Recently, satellite estimates are being assimilated into NWP models to improve the NWP forecasts by providing more observations at regular intervals.

5.09.4 Summary and Concluding Remarks

Water resources decision making in semiarid regions is driven by the need to have reliable water supplies of adequate quality, in the face of stressed surface water and dwindling groundwater supplies. In managing water resources, accurate and uninterrupted information on the quantity of water cycle components is critical for sustainable development. Given the population growth, industrial development, and increasing challenges for sustainable water resources management, innovative approaches to quantify hydrologic variables are highly desirable. In recent years, remote sensing data sets have emerged as major sources of information on hydrologic variables. In the past decades, utilization of remote sensing data in water resources and water cycle studies has increased significantly.

Several climate projections indicate an increase in drought frequency, duration, and severity in the future (WCRP 2010). A major challenge in the development of drought monitoring systems is the lack of information on the indicator variables (e.g., precipitation, soil moisture, and storage). In this chapter, a drought model based on PERSIANN remotely sensed precipitation data is introduced. In a case study, SPIs were estimated for the contiguous United States using PERSIANN precipitation data. The results indicated that the general patterns of wet and dry areas from PERSIANN data were in reasonable agreement with those obtained from gauge data.

One attractive feature of PERSIANN precipitation estimates for drought analysis is the possibility of reconstructing long-term data required for studying droughts. Currently, efforts are underway to provide PERSIANN data continuously for the past 30 years for which IR images are available. We anticipate that the high-resolution, multidecadal PERSIANN data will provide a valuable source of data for quasi-global drought analysis.

Application of PERSIANN and PERSIANN-MBA data sets in streamflow simulation has been discussed in a case study. Previous studies reveal that most unadjusted precipitation data sets, including PERSIANN, tend to overestimate precipitation, particularly over warm months (AghaKouchak et al. 2011; Behrangi et al. 2011). The overestimations (bias) of most satellite precipitation data sets are typically more significant for higher precipitation rates (high quantiles). This limits the application of satellite data in streamflow simulation. The results indicated that the simulated streamflow using the original PERSIANN precipitation data overestimates observed data. Simulated discharge using PERSIANN-MBA, on the other hand, exhibits significant improvement in capturing runoff peaks. Notice that gauge-corrected PERSIANN-MBA is only available at the end of the month as the bias correction is performed in monthly scale. Therefore, this product is not available for real-time analysis.

It is worth pointing out that major achievements have been made in model development; however, without reliable input data (e.g., precipitation), models cannot provide meaningful simulations. Satellites can provide precipitation data over remote locations and ungauged basins, as well as areas with complex terrain where no other means of measurement is available. Given the importance of the quality of input precipitation in hydrological modeling, we predict that in the near future more efforts will be devoted to improve satellite precipitation estimates by using multisensor multispectral approaches.

As mentioned earlier, remotely sensed data sets have several advantages over ground-based measurements such as higher spatial resolution and uninterrupted measurement (e.g., better overall estimation of space–time variability of precipitation). However, these data sets have not yet fully integrated into water resources management and decision-making systems, mainly because of undetermined uncertainties (Hossain and Huffman 2008; Margulis et al. 2006; AghaKouchak et al. 2010b; Dong et al. 2005; Lucieer and Kraak 2004; Bastin et al. 2002; Crosetto et al. 2001). Thus far, extensive research has been devoted to validate and improve satellite precipitation data including PERSIANN data (e.g., Stisen and Sandholt 2010; Shen et al. 2010; Tian et al. 2009; Zeweldi and Gebremichael 2009; Feidas et al. 2009; Liu et al. 2009; Sapiano and Arkin 2009; Durga Rao et al. 2009; Turk et al. 2008; Tuttle et al. 2008; Dinku et al. 2008; Ebert et al. 2007).

We believe that more efforts should be devoted to the validation and verification of satellite data in order to identify the limitations and further develop the data sets for practical applications. While application of satellite precipitation data in water resources and decision making seems to be promising, a great deal of research is necessary to further improve the quality of satellite data for hydrologic applications (e.g., development of more sophisticated bias-adjustment techniques). Furthermore, efforts are required to quantify uncertainty of satellite data, which is a roadblock in the application of satellite data in water resources applications (AghaKouchak et al. 2011; Hossain and Huffman 2008; Margulis et al. 2006; Dong et al. 2005; Hossain and Anagnostou 2005).

As mentioned earlier, global climate models assess potential climatic change impacts on the water cycle. However, climate model outputs have many limitations for operational applications including coarse resolution. It is our view that sustainable water resources management requires tools beyond global climate modeling. Advanced methodologies should be developed along with high-resolution and reliable data sets in scales relevant to operational water resources management (Pielke et al. in press; Sorooshian et al. 2011). It is hoped that future research toward high-resolution quantitative multisensor precipitation with quantified uncertainty leads to a significant advance in water resources management.

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5.10 Application of Satellite Gravimetry for Water Resource Vulnerability Assessment

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5.10.1 Introduction

The force of gravity is directly proportional to mass. Although we may think of gravity as being a constant at 9.8 m s^{-2}, mass is not uniformly distributed at the Earth's surface and therefore gravity is nonuniform as well. Earth's gravity field can be visualized as a bumpy ellipsoid, having both static and time-variable components, the static component being orders of magnitude stronger. Jeffreys (1952) was among the first to report the existence of the time-variable component, noting that mass movements such as ocean tides changed the gravity field.

From the perspective of an orbiting satellite, the Rocky Mountains exert more gravitational force than the Great Plains and eastern Asia exerts more gravitational force during monsoon season, when the ground is wet and therefore more dense, than during the dry season. The orbit of such a satellite is perturbed in a way that can be predicted based on the gravitational potential and thus, the surface mass distribution, or vice versa. Realizing this, scientists began to use the orbits of artificial satellites to identify spatial irregularities in the Earth's gravity field in the late 1950s. Satellite tracking via optical and Doppler techniques allowed them to compute departures from predicted orbits, and from these values, the static gravity field was mapped. In the 1960s, satellite laser ranging enabled more accurate determination of satellite orbits and thus more detailed assessments of the gravity field. Yoder et al. (1983) reported that the orbit of the Lageos satellite was sensitive to temporal variations in the gravity field, which was a first glimpse at the future of time-variable gravity field mapping.

For the purpose of mapping Earth's time-variable gravity field with enough accuracy to be useful for such applications as ocean, ice sheet, and terrestrial hydrology monitoring, geodesists realized that tracking satellite orbits from the surface was too imprecise. Instead, they concluded that a dedicated twin satellite gravimetry mission, with each satellite tracking the orbit of the other, was the best strategy (Dickey et al. 1997). Plans for the Gravity Recovery and Climate Experiment (GRACE) satellite mission soon followed.

GRACE, launched on 17 March 2002, was sponsored jointly by NASA and its German counterpart. In addition to improving the resolution and accuracy of global gravity maps by more than two orders of magnitude, GRACE proved to be immensely valuable for oceanography, cryospheric science, and hydrology. Perhaps the most renowned climate-related application of GRACE is the estimation of mass losses from the Greenland and Antarctic ice sheets and the associated sea level rise (e.g., Velicogna and Wahr 2006a,b; Luthcke et al. 2006). Similarly, GRACE has measured the ablation of major glacier systems in Alaska (Tamisiea et al. 2005; Luthcke et al. 2008), South America (Chen et al. 2007), central Asia (Matsuo and Heki 2010), and the Canadian Arctic Archipelago (Gardner et al. 2011). GRACE has also contributed to numerous studies in many areas of hydrology, including river discharge estimation (Syed et al. 2009), regional evapotranspiration (Rodell et al. 2004; Swenson and Wahr 2006a), hydroclimatic teleconnections (Andersen et al. 2005; Crowley et al. 2006), groundwater variability (Yeh et al. 2006; Rodell et al. 2007), and drought monitoring (Houborg et al. 2012).

Thus, satellite gravimetry as demonstrated by GRACE lends itself to the study of climate vulnerability, particularly water resources change. This chapter provides details of the GRACE mission and the data it provides (see Section 5.10.2); describes examples of GRACE-enabled investigations of hydroclimate and hydroresources variability including groundwater (see Section 5.10.3), surface waters, and glaciers (see Section 5.10.4), integration of GRACE and other data within numerical models (see Section 5.10.5), and drought monitoring; and reports on future prospects of satellite gravimetry.

5.10.2 GRACE Data: Unique and Challenging

The GRACE mission consists of two satellites in a near-polar orbit, about 200 km apart, at a starting altitude of about 500 km. The precise distance between the satellites is constantly measured using a K-band microwave ranging system. The range measurements along with positioning data are used to construct a new map of Earth's gravity field each month, represented mathematically by a set of spherical harmonic coefficients describing the shape of the global gravity field (Tapley et al. 2004). From these monthly 'gravity field solutions,' time series of regional mass anomalies can be derived using specially designed averaging functions (Wahr et al. 1998).

Unlike conventional remote sensing techniques that rely on measurements of various wavelengths of light emitted or reflected from the Earth's surface, vegetation, or atmosphere, satellite gravimetry is not blind to subsurface conditions. GRACE senses variations in the total mass from the top of the atmosphere to the center of the Earth. Oceanic and atmospheric circulations and redistribution of terrestrial water via the hydrological cycle are the main sources of gravitational variability on time scales of months to years. Numerical model analyses are used to estimate and remove the oceanic and atmospheric effects, leaving variations in terrestrial water storage (TWS; the sum of groundwater, soil moisture, surface water, snow, ice, and vegetation biomass) as the only major signal over land. Glacial isostatic adjustment also must be taken into account in certain regions such as Hudson's Bay in Canada and the Scandinavian peninsula, and the Sumatra–Andaman earthquake of 2004 and the Japanese Tohoku earthquake of 2011 produced huge abrupt gravitational anomalies in those regions. However, the time scales of most solid earth processes are too long to be relevant.

What has made GRACE uniquely valuable to hydrology is its ability to measure variations in total water availability on and in the land surface, without limitations of depth, visibility, or location on the Earth. However, the satellite gravimetry method has its own set of challenges. First, instead of having a remote sensing footprint or pixel resolution, there is a tradeoff between resolution and accuracy. The gravity field solutions contain larger errors at higher degrees and orders (smaller length scales). At resolutions finer than about 150 000 km^2, the uncertainty in the estimates overwhelms the retrieved mass variations (Rodell and Famiglietti 1999; Rowlands et al. 2005; Swenson et al. 2006). Second, measuring changes in all components of TWS at once is a double-edged sword. GRACE provides no information on the vertical structure of a TWS change, whether in the saturated zone, shallow subsurface, surface waters, or ice and snow cover. Third, most hydrologists are accustomed to working with instantaneous or daily observations of an absolute quantity, such as rainfall rate or snowpack depth, whereas GRACE provides monthly mean estimates of TWS anomalies (deviations from the long-term average). A related issue is that a monthly observational cycle (for the standard products) ensures that GRACE data will never be available close to real time. The standard products are typically available a couple of months after the fact. Development of an expedited product is being studied by the GRACE science team, but that still would not meet the needs of most operational water resources and weather-related applications.

5.10.3 Groundwater Depletion Assessment

Clearly, real-time data are not required for all applied or scientific hydrology applications. Quality and duration of observations are more important for assessing groundwater variability and depletion. In order to employ GRACE data for this purpose, groundwater storage must be isolated from the other components of TWS. A simple approach is to use auxiliary data to estimate variations in soil moisture and snow water equivalent and to subtract these from TWS variations, leaving variations in groundwater storage as a residual. The assumption here is that temporal variability of vegetation biomass and surface water storage is negligible relative to that of groundwater, soil moisture, and, depending on the region, snow mass. Rodell et al. (2005) demonstrated that seasonal and interannual changes in biomass are at or below the limits of detection by GRACE. Outside humid tropical regions such as the Amazon (Han et al. 2009) and Bangladesh (Shamsudduha et al. 2012), surface water storage mass variations are also typically insignificant relative to soil moisture, groundwater, and snow mass variations (Rodell and Famiglietti 2001; Rodell et al. 2009). However, networks of soil moisture (and snow) measurement sites that are dense enough to construct reliable time series of regional mean water storage variability are rare (e.g., Yeh et al. 2006). Rodell et al. (2007) demonstrated that soil moisture and snow time series from numerical land surface models (LSMs) were a reasonable alternative, deriving a time series of groundwater storage in the Mississippi River basin that compared favorably with a time series based on groundwater well observations.

The High Plains aquifer of the central United States, whose groundwater depletion is well documented (e.g., Luckey et al. 1981), provides a useful case study for evaluating the ability of GRACE to monitor interannual variations in groundwater storage. As in many other agricultural regions where rainfall is frequently insufficient to support crop production demands, groundwater withdrawals for irrigation exceed recharge over the long term. This has caused the water table to decline at an average rate of about 7.2 cm year^{-1} since 1950, which is equivalent to a reduction in water storage of 337 km^3 between 1950 and 2009 (McGuire 2011). The rates of water table decline are greater in the central and southern parts of the aquifer, reaching more than 80 cm year^{-1} in some areas of the Texas panhandle.

Strassberg et al. (2007) combined GRACE TWS observations with soil moisture output from the Global Land Data Assimilation System (GLDAS; Rodell et al., 2004) to compute groundwater variations in the High Plains aquifer during 2003–2005. The correlation coefficient between observed and GRACE-derived monthly groundwater storage was determined to be 0.58, although the time period was too short to assess the efficacy of the GRACE technique for monitoring interannual variability. A subsequent analysis by Strassberg et al. (2009) improved on those results in a study covering the period 2003–2007 with a more optimally derived GRACE TWS time series and both observational and model-based soil moisture data, achieving correlation coefficients of 0.73 and 0.72, respectively, between observed and GRACE-based monthly groundwater storage time series.

Another area of the United States that may be overly dependent on groundwater is California's Central Valley. Thanks to its favorable climate and good soil, the Central Valley supports a wide variety of crops and is considered one of the most productive agricultural regions of the world. However, sustaining this productivity requires a rate of rainfall that is not consistently available and may be well short during dry years. The proximal solution is fed by irrigation by water from the aquifer beneath the Sacramento and San Joaquin river basins, which are mainly recharged by melting snow from the Sierra

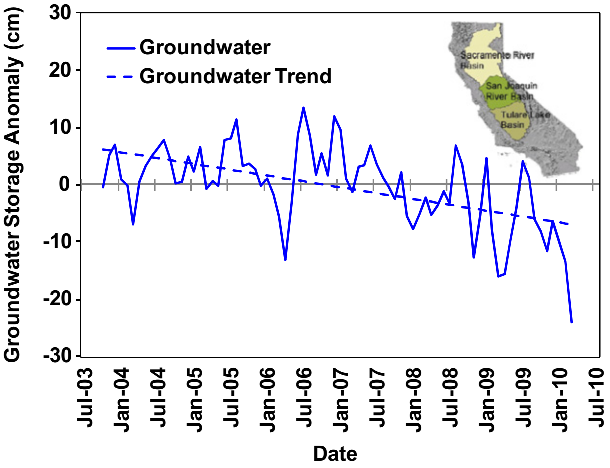

Figure 1 Time series of GRACE-estimated groundwater anomalies (with linear trend) as an equivalent height of water in centimeters, averaged over California's Sacramento, San Joaquin, and Tulare lake basins (inset). Source: Modified from Famiglietti, J. S., and Coauthors, 2011: Satellites measure recent rates of groundwater depletion in California's Central Valley. *Geophys. Res. Lett.*, **38**, http://dx.doi.org/10.1029/2010GL046442.

Nevada Mountains (Faunt 2009). Famiglietti et al. (2011) used GRACE data spanning October 2003–March 2010 to estimate that the Sacramento and San Joaquin river basins (154 000 km^2) lost water at an average rate of 4.8 km^3 year^{-1} (Figure 1), about two-thirds of which was groundwater pumped from the Central Valley. They concluded that groundwater depletion at this rate was unsustainable and would have serious consequences if unabated. Fortunately for California, exceptionally wet weather during the winter of 2010–2011 helped the Central Valley aquifer to recuperate to some extent, delaying those consequences for the time being.

The starkest example of groundwater mining over a large area is in northern India. Such a massive quantity of water is being removed from this region that it stands out like a bull's eye on a global map of trends in the gravity field derived from GRACE data (Figure 2). Although officials in India have long been aware that groundwater withdrawals exceed recharge on annual average across the Indian states of Rajasthan, Punjab, and Haryana (including Delhi), an integrative assessment of the rate of depletion had not been performed before the onset of GRACE. Rodell et al. (2009) used GRACE TWS data and simulated soil moisture from the GLDAS to determine that groundwater was depleted at a mean rate of 17.7 ± 4.5 km^3 year^{-1} between August 2002 and October 2008 over the 438 000 km^2 region (Figure 3). This equates to 4.0 ± 1.0 cm year^{-1} equivalent layer of water (about 33 cm of water table decline per year) and a total of 109 km^3 of groundwater during the study period, which is triple the capacity of Lake Mead, America's largest man-made reservoir. Annual rainfall was close to normal throughout the period, which rules out the possibility of drought-related TWS diminishment, and it was determined that surface water and other TWS components did not contribute significantly to the observed trend. Analyzing a 2 700 000-km^2 surrounding area of northern India in a similar GRACE-based study, Tiwari et al. (2009) estimated a groundwater depletion rate of 54 ± 9 km^3 year^{-1}. Currently, farmers are given free electricity for groundwater pumping, so there is no incentive for conservation, yet there is great resistance to changing this policy. The desire for water-intensive crops, rice in particular, exacerbates the problem. A sustainable solution to avert hydrological and agricultural catastrophe for the 600 million residents of the broader region will require creativity, political will, and, above all, acceptance of the need for change.

A similar situation exists just to the east in the Bengal basin of Bangladesh. Groundwater abstraction for irrigating dry season rice crops along with reduced recharge because of urbanization has depleted the aquifers over the past 40 years. Groundwater abstraction is believed to mobilize arsenic, putting further pressure on this vital yet vulnerable resource (Ahmed et al. 2004). It is unclear how future climate change (e.g., if the South Asian monsoon shifts in location or intensity) would affect groundwater storage dynamics. Shamsudduha et al. (2012) compared ground-based observations with GRACE TWS data and confirmed that GRACE captures both the seasonality and the trend of groundwater storage in the Bengal Basin, making it valuable for water resources assessment in the region. They found that groundwater storage accounted for the greatest proportion of total variability in TWS in the basin, at 44%, with soil moisture and surface water storage accounting for 33% and 22% of variability, respectively. The rate of groundwater depletion based on GRACE observations during 2003–2007 was estimated to be 0.5 ± 0.3 km^3 year^{-1}.

5.10.4 Lakes and Glaciers

Inland surface waters are another resource that is vulnerable to overexploitation and drought, effects that can be detected by GRACE if the mass changes are large enough. Seasonal water storage changes in the Amazon River system are the largest in the world, and interannual variability, mainly because of El Niño Southern Oscillation cycles, is similarly immense. Because Amazon surface waters are often dispersed across the landscape rather than concentrated in distinct river channels, ground-based quantification of total storage and flow volumes is imprecise. Thus, several studies have applied GRACE observations to refine understanding of water cycle variability and surface water dynamics in the Amazon River basin (e.g., Han et al. 2009; Alsdorf et al. 2010). Awange et al. (2008), Swenson and Wahr (2009), and Becker et al. (2010) used GRACE to study water level changes in east African lakes, which are affected by both climatic variability and water resources management, both poorly documented. Swenson and Wahr (2009) used GRACE data together with satellite-altimetry-based lake levels to infer the water balance of Lake Victoria and the surrounding region. Results were compared with reservoir management data as available and results from previous studies. They concluded that at least half of the observed lake level declines during 2002–2006 were caused by releases from Lake Victoria's dams in excess of amounts approved via international treaty (lake discharge being used for hydroelectric power generation). Other surface water bodies whose water storage variability has been elucidated by GRACE include the

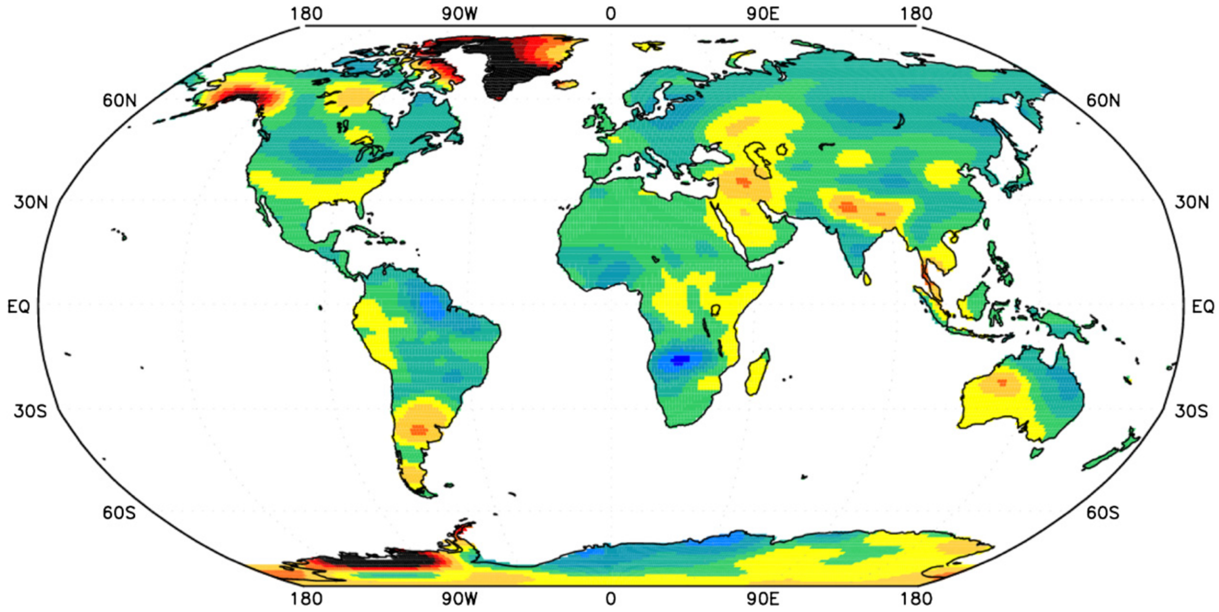

Figure 2 Mean rates of change ('trends') of terrestrial water storage (centimeters per year) based on GRACE data from August 2002–August 2011. The effects of postglacial rebound have been removed from the GRACE data using the model of Paulson et al. (2007), but the gravitational effects of major earthquakes in Sumatra (2004) and Japan (2009) distort the estimated trends near those locations.

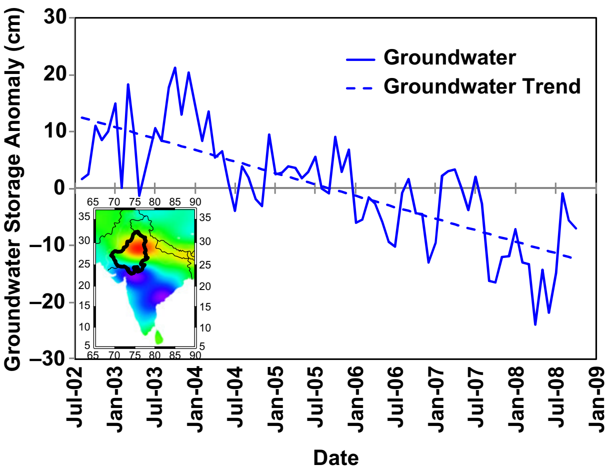

Figure 3 Time series of GRACE-estimated groundwater anomalies (with linear trend) as an equivalent height of water in centimeters, averaged over the Indian states of Rajasthan, Punjab, and Haryana. The inset outlines the region in black on a map of groundwater trends, with depletion in warmer shades. Source: Modified from Rodell, M., I. Velicogna, and J. S. Famiglietti, 2009: Satellite-based estimates of groundwater depletion in India. *Nature*, **460**, 999–1002, http://dx.doi.org/10.1038/nature08238.

Caspian Sea (Swenson and Wahr 2007), Lakes Baikal and Balkhash (Hwang et al. 2011), and the Three Gorges Reservoir (Wang et al. 2011).

Glaciers store freshwater and release it gradually in warm seasons, making them an important resource that happens to be very susceptible to climate variability and longer-term change. Over the past decade or more, several of the world's major glacier systems have been melting fast enough such that the associated mass change signals are observable by GRACE. While thinning of Greenland's ice sheet has attracted most of the attention in the Arctic region (e.g., Velicogna and Wahr 2006a,b; Luthcke et al. 2006), Gardner et al. (2011) recently made use of GRACE to determine that the melt rate from ice caps and glaciers of the Canadian Arctic Archipelago is equivalent to about 61 km^3 year^{-1} of water, or 0.17 mm year^{-1} sea level rise. For comparison, Greenland loses about 219 km^3 year^{-1}, or 0.61 mm year^{-1} sea level rise (Chen et al. 2011). Tamisiea et al. (2005) and Luthcke et al. (2008) showed that glaciers along the southern coast of Alaska are melting at a rate of about 84 km^3 year^{-1} (0.23 mm year^{-1} sea level rise). Chen et al. (2007) calculated that Patagonian glaciers in southern South America are losing 28 km^3 year^{-1} (0.08 mm year^{-1} sea level rise). Matsuo and Heki determined using GRACE that ice water storage losses from the Tibetan Plateau were at least 47 km^3 year^{-1} (0.13 mm year^{-1} sea level rise) during 2003–2009, which is double the estimated rate of the preceding 40 years, and that the rate could be as high as 61 km^3 year^{-1} depending on glacial isostatic adjustment beneath the plateau.

5.10.5 GRACE Data Assimilation

While the previous sections clearly demonstrate that GRACE observations have been valuable for a range of hydrological studies, decision support and most other applied disciplines require data that have higher resolution and are available closer to real time. With this as the motivation, Zaitchik et al. (2008) introduced a more sophisticated approach for spatially, temporally, and vertically disaggregating GRACE-derived terrestrial water storage while simultaneously allowing the information to be extended to near real time. The approach

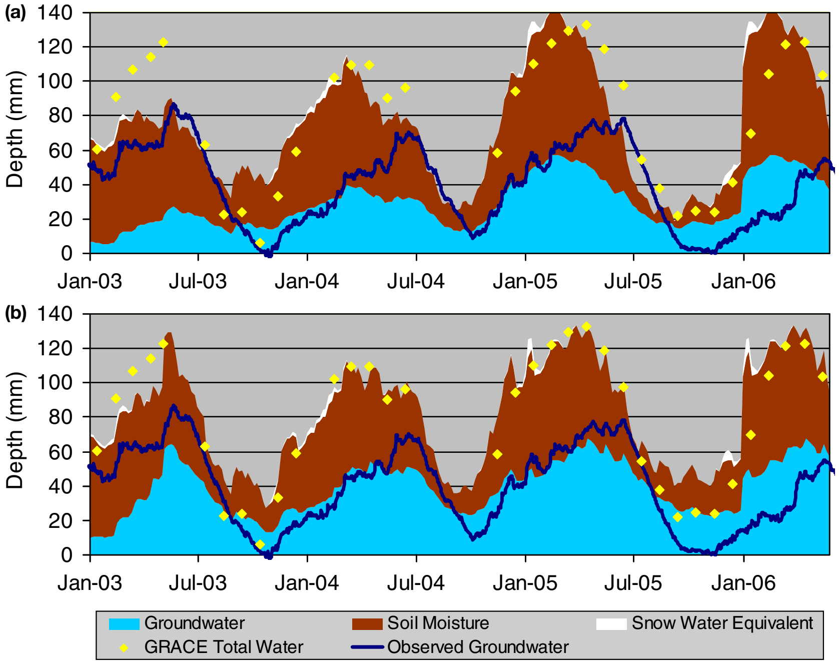

Figure 4 Groundwater, soil moisture, and snow water equivalent averaged over the Mississippi River Basin from (a) open loop Catchment land surface model and (b) GRACE data assimilation. Also shown are daily observation-based groundwater and monthly GRACE-derived TWS anomalies. GRACE and modeled TWS were adjusted to a common mean, as were observed and modeled groundwater. The correlation coefficient between simulated and observed groundwater improved from 0.59 (open loop) to 0.69 (GRACE-DAS). Unlike GRACE alone, the assimilated product is 3-hourly and vertically distributed. Source: Modified from Zaitchik, B. F., M. Rodell, and R. H. Reichle, 2008: Assimilation of GRACE terrestrial water storage data into a land surface model: results for the Mississippi River Basin. *J. Hydrometeor.*, **9**(3), 535–548, http://dx.doi.org/10.1175/2007JHM951.1.

employs an ensemble Kalman smoother to assimilate GRACE data into a numerical LSM. This has several advantages. First, physical equations of hydrologic and energetic processes, integrated within the model, provide a basis for synthesizing GRACE and other relevant observations (e.g., precipitation, solar radiation, land cover) in a physically consistent manner. Second, the model fills spatial and temporal data gaps, while observations anchor the results in reality. Third, in addition to separating groundwater, soil moisture, and snow, the assimilated output has much higher spatial and temporal resolutions than the original GRACE data. Zaitchik et al. (2008) selected the Catchment LSM for this purpose, mostly because it simulates groundwater storage variations, a prerequisite that most models do not satisfy. They chose to use an ensemble Kalman smoother rather than the more common Kalman filter because the filter assimilates observations as they become available and updates only the most recent model states, whereas smoothers use information from a series of observations to update model states over a window of time (Dunne and Entekhabi 2005; Evensen and van Leeuwen, 2000). Smoothers are therefore well suited for GRACE observations, which are noninstantaneous. Before assimilation, GRACE TWS anomalies are converted to absolute TWS values by adding the corresponding regional time-mean water storage from the open loop (no data assimilation) portion of the Catchment model simulation. Zaitchik et al. (2008) validated the technique in the Mississippi River basin using groundwater data from a network of wells and showed significant improvement in both the timing and amplitude of modeled groundwater variations (Figure 4). The correlation coefficient between the simulated and observed groundwater storage time series improved from 0.59 to 0.69 because of GRACE data assimilation. Furthermore, it was shown that GRACE data assimilation affects modeled evapotranspiration and runoff fluxes. In addition to drought monitoring (described in the next section), GRACE data assimilation has now been applied for snowpack quantification in the Mackenzie River basin (Forman et al. 2012), water cycle characterization in western Europe (Li et al. 2012), and water resources assessment in the Middle East and North African region (Bolten et al. 2010).

5.10.6 Drought Monitoring

Drought has devastating impacts on society and costs the US economy 6–8 billion dollars per year on an average (WGA 2004). Drought affects the availability of water for irrigation, industry, and municipal usage; it can ravage crops, forests, and other vegetation, and, where rivers support hydropower and power plant cooling, it affects electricity generation. Most current drought products rely heavily on precipitation indices and are limited by the scarcity of reliable objective information on subsurface water stores. Groundwater levels, which integrate meteorological conditions over time scales of weeks to years, would be particularly well suited to drought monitoring, if only such data were available with some semblance of spatial

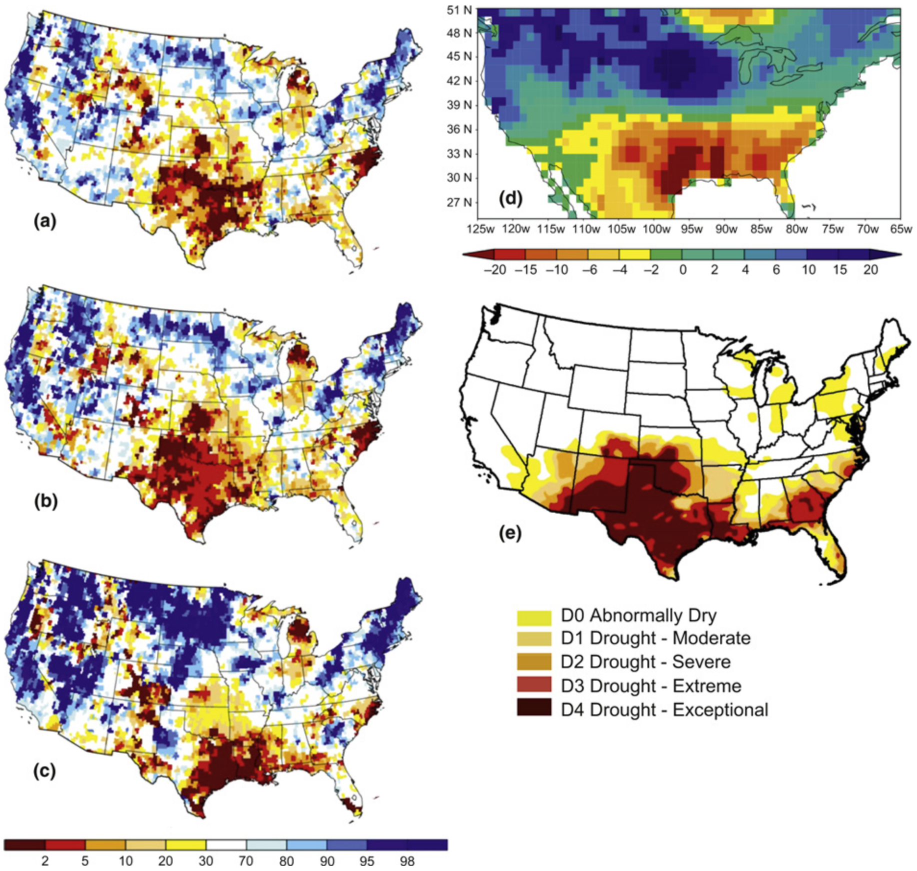

Figure 5 GRACE-based drought indicators (wetness percentiles) of surface soil moisture (a), root zone soil moisture (b), and groundwater (c) for 27 July 2011, compared with the GRACE terrestrial water storage anomalies (centimeter equivalent height of water) for July 2011 (d) and the US Drought Monitor product for 26 July 2011 (e). Source: Li, B., M. Rodell, B. F. Zaitchik, R. H. Reichle, R. D. Koster, and T. M. van Dam, 2012: Assimilation of GRACE terrestrial water storage into a land surface model: evaluation and potential value for drought monitoring in Western and Central Europe. *J. Hydrol.*, **446–447**, 103–115, http://dx.doi.org/10.1016/j.jhydrol.2012.04.035.

and temporal continuity and a reasonably long background climatology (Rodell 2010).

Droughts cause declines in all types of terrestrial water storage, and as a result, they stand out in the GRACE data. For example, drought in the southeastern United States (2007–2008) imparted a negative trend in that area in Figure 2. GRACE has been applied directly to investigate a decade long drought in southeastern Australia (Awange et al. 2009; Leblanc et al. 2009). Yirdaw et al. (2008) characterized TWS changes associated with a recent drought in the Canadian prairie. Chen et al. (2009) used GRACE to study a major drought event in the Amazon that occurred in 2005, and Chen et al. (2010) examined a recent drought in the La Plata Basin.

Houborg et al. (2012) applied the GRACE data assimilation approach to enhance the value of GRACE for drought monitoring, developing surface and root zone soil moisture, and groundwater drought indicators for the continental United States. Because a long-term record is needed as background to quantify drought severity, whereas GRACE data are only available from mid-2002, it was necessary to rely on the Catchment LSM alone for most of the record. Therefore, Houborg et al. (2012) executed an open loop model simulation for the period 1948 to near present using for input a meteorological forcing dataset developed at the Princeton University (Sheffield et al. 2006). Monthly GRACE TWS anomaly fields (Swenson and Wahr 2006b) were converted to absolute TWS fields by adding the time-mean total water storage field from the open loop Catchment model simulation. This assured that the assimilated TWS output would be nearly identical to that of the open loop, which is to say that there was no discontinuity between the open loop and assimilation portions of the run. However, the GRACE data, and therefore the assimilation results, could still have a larger or smaller range of variability than the open loop land surface model (LSM) results at any given location. This is significant because drought monitoring concerns the extremes. Therefore, to correct for differences in the range of variability between the assimilation and the open loop model output, Houborg et al. (2012) computed and mapped between the cumulative distribution functions of wetness at each model pixel for the open loop and assimilation results during the overlapping period (2002 onward). Drought indicator fields for surface (top several centimeters) soil moisture, root zone soil moisture, and groundwater were then generated based on the probability of occurrence in the output record since 1948. To mimic other drought indicators that contribute to the US Drought Monitor product, dry conditions were characterized from D0 (abnormally dry) to D4 (exceptional), corresponding to decreasing cumulative probability percentiles of 20–30%, 10–20%, 5–10%, 2–5%, and 0–2%. Following this process, new GRACE-data-assimilation-based drought indicators (Figure 5) are now being produced on a weekly basis by NASA and disseminated from the University of Nebraska's National Drought Mitigation Center web portal. They are also being delivered to the principals of the US Drought Monitor, who are currently assessing them as new inputs. The US Drought Monitor is the premier decision support tool for drought in the United States; however, it lacked spatially continuous groundwater and soil moisture inputs before the development of the new GRACE-based drought indicators. Currently, there are very few drought assessment products available that have global coverage, and those that do exist lack the sort of information on subsurface water stores that GRACE provides. It is likely that the GRACE-based drought indicators just described will be extended to the global scale in the near future to help alleviate this knowledge gap.

5.10.7 Future Prospects

Satellite gravimetry is the only remote sensing technology currently available for measuring water stored below the first few centimeters of the soil column or the total liquid and frozen water storage. In addition to GRACE, two other advanced gravity monitoring satellites have been launched: Germany's Challenging Minisatellite Payload (CHAMP) in 2000 and the European Space Agency's Gravity Field and Steady-State Ocean Circulation Explorer (GOCE) in 2009. CHAMP and GOCE each significantly advanced the capability to map the static gravity field at their times of launch, GOCE with significantly higher spatial resolution than GRACE, but neither was suitable for monitoring the time-variable gravity field and inferring changes in TWS (Han and Ditmar 2008).

GRACE has endured well beyond its designed 5-year mission lifetime, and there is no set end date. Depending on battery and instrument health and fuel consumption for orbital adjustments, the mission might continue into the middle of the 2010s. NASA, Germany's space agency, the European Space Agency, and various other organizations have begun discussions of a next-generation satellite gravimetry mission, which would improve on GRACE's horizontal resolution by up to an order of magnitude. This could be achieved by replacing the microwave ranging system with a laser interferometer, flying at a lower altitude in atmospheric-drag-free spacecraft (NRC 2007), and possibly maintaining multiple satellite pairs in orbit simultaneously (Wiese and Nerem 2011). While the improved resolution would be valuable, the need for further downscaling via data assimilation would remain. In the meantime, NASA has begun the development of a follow-on to GRACE with a nearly identical mission design, which would provide continuity in the data record while affording some improvement in resolution because of basic technological advancements of the past 10 years (Watkins et al. 2011). This mission could launch as soon as 2016 and enable gravimetry-based water availability monitoring into the next decade.

Water is essential to life and vulnerable, for example, to overexploitation, pollution, and redistribution associated with any changes in precipitation and temperature. The information provided by GRACE and future satellite gravimetry missions has great potential to improve monitoring and understanding of freshwater availability, thereby helping to reduce environmental and social consequences. The hydrology and other climate communities have been somewhat slow to embrace GRACE as a tool of the trade because of the unique and challenging aspects of the observations. However, success stories such as those described here are increasing awareness and building momentum for GRACE-enabled research and applications. Extending the data record by maintaining GRACE and launching the GRACE follow-on mission will also reduce uncertainty in and improve the understanding of climatic and anthropogenic impacts on the water cycle that have begun to be revealed. Hopefully, as these impacts become less equivocal, stakeholders and policymakers will make better decisions and reduce threats to our precious freshwater resources.

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5.11 Changing Discharge Patterns of High-Latitude Rivers

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Glossary

Hydrograph A time series showing the changes of river flow.

Pan-Arctic The northern land mass defined by all drainage basins flowing to the Arctic Ocean and northern seas.

River Discharge The volume of water passing through a specific cross section of river during a specific time (examples include $m^3\ s^{-1}$ and $km^3\ year^{-1}$).

Runoff The area normalized river discharge over a defined drainage area. Units are expressed as a depth, typically in mm.

Stage height Measured water level of a river used to determine the volume of flow.

5.11.1 Introduction

The Arctic is undergoing marked changes in response to climate. Numerous studies indicate that the global climate signal in the Arctic is pronounced and has already exceeded natural climate variability (ACIA 2005). All components of the arctic ecosystem are intimately linked to all others and water plays a central and unique role in this system. There is mounting evidence that the region is experiencing an unprecedented degree of environmental change in various components of the water cycle. These include loss of permafrost (Yang et al. 2002); change in river flow volume (Lammers et al. 2001; Peterson et al. 2002; Shiklomanov and Lammers 2009) and timing (Shiklomanov et al. 2007; Tan et al. 2011); lengthened ice-free periods in lakes and rivers (Magnuson et al. 2000; Vuglinsky 2002); disappearance of lakes (Smith et al. 2005); reductions in snow cover (Armstrong and Brodzik 2001); and melting of glaciers (Steffen et al. 2004). Streamflow changes are strongly related to climate variability, disturbance in land cover, degradation of the cryosphere, and direct human impact. River flow is an integrated characteristic reflecting numerous environmental processes and their changes aggregated over different size areas. River runoff also plays a significant role in the freshwater budget of the Arctic Ocean (Serreze et al. 2006). Ocean salinity and sea ice formation are critically affected by river input. Changes in the freshwater flux to the Arctic Ocean can exert significant control over global ocean circulation by affecting North Atlantic deep water formation (Manabe and Stouffer 1994; Rahmstorf 2002). Arctic drainage basin river flow is thus likely to serve an important role in regulating the heat balance of the planet (Peterson et al. 2006). The freshwater cycle of the Arctic therefore takes on a central role in our understanding of the influence of global change on terrestrial ecosystems and on the connection of the northern land mass to the Arctic Ocean (Lammers et al. 2001).

5.11.1.1 Definition of Domain

Our understanding of the Arctic Ocean's freshwater budget variability requires analysis of hydrological processes across the entire river runoff formation zone covering both the Arctic Ocean watershed and the adjacent territories from which the runoff contributes to the ocean freshwater budget. The entire Pan-Arctic hydrological domain covers a region of approximately 24 million km^2(including Greenland) and represents a significant part of the global land surface in the north. The region is characterized and defined hydrologically by the north flowing rivers entering the Arctic Ocean, Hudson Bay, James Bay, the Canadian Arctic Archipelago, the far north Atlantic Ocean, and Bering Strait including much of Alaska (Shiklomanov et al. 2000; Lammers et al. 2001; Forman et al. 2000) (**Figure 1**). Although the Hudson Bay, James Bay, and Bering Strait are located outside of the Arctic Ocean drainage basin, the rivers draining into these water bodies supply a large amount of freshwater discharge to the Arctic Ocean via the north-flowing oceanic currents (AMAP 1998). Thus, it is important to take into account the river discharge from these drainage basins when assessing the dynamics of the river flux into the Arctic Ocean. The headwaters of the large Arctic rivers such as Nelson, Ob, and Yenisey drainage basins extend halfway to the equator to a latitude of 45°N. Thus, a significant

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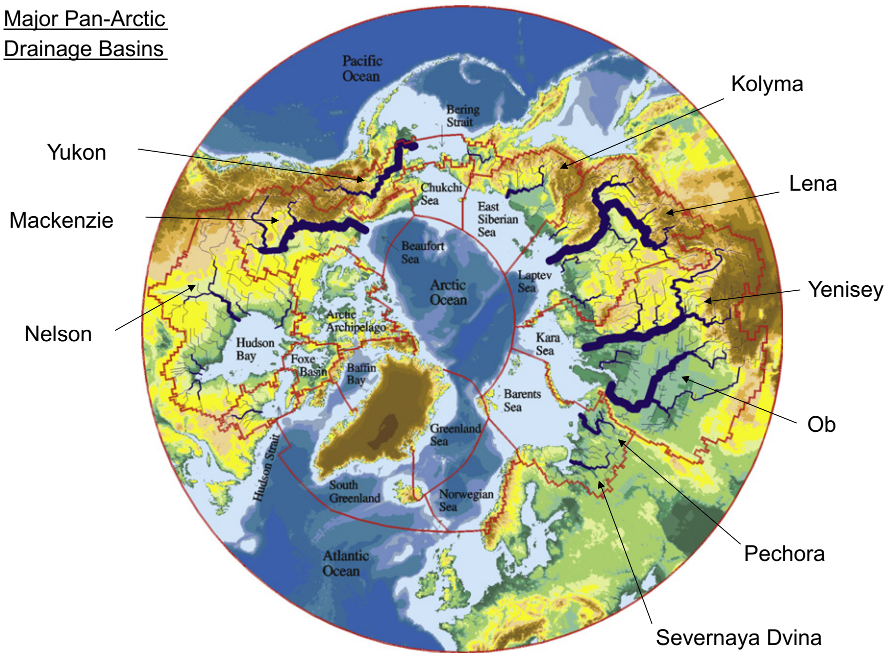

Figure 1 Major northern rivers (dark blue lines) and seas (red outlines) of North America and Eurasia. Background coloring shows elevation and bathymetry relative to sea level. Forman, S. L., W. Maslowski, J. T. Andrews, D. R. Lubinski, M. Steele, J. Zhang, R. Lammers, and B. Peterson, 2000: Researchers explore arctic freshwater's role in ocean circulation. *EOS Trans. Am. Geophys. Union*, **81**, 169–174.

part of the Pan-Arctic hydrological domain is located in temperate climate zones and is covered not only by tundra, but also by boreal–taiga forest and grassland.

5.11.2 Current Status of Discharge Monitoring

This section explores the status of river monitoring at high latitudes, what data is being collected, how good this data is, what parts of the domain are regularly monitored, and how have changes in the gauging network altered over time. Each of these components is critical to understanding the true nature of the observed changes and how these have impacted the humans in the northern latitudes.

Access to comprehensive and reliable data on Arctic hydrology is of crucial importance for studies focusing on the role of the Arctic in the climate system. The rivers draining to the Arctic Ocean redistribute moisture from temperate regions to the high latitudes, and also connect very large and heterogeneous areas to the Arctic Ocean and its shelf seas (Arctic-HYDRA 2010).

Few of the major measured components of the hydrological cycle are considered to have sufficient accuracy to support a full closure of the water budget. Groundwater fluxes tend to be poorly known and evapotranspiration is rarely measured in sufficient sampling density over large regions. Measurement of rainfall is carried out more regularly, but in cold regions this only accounts for a fraction of total precipitation. Solid precipitation measurement is known to have large systematic and random errors, often with large uncertainties arising from the use of imperfect gauging techniques (Goodison et al. 1998). The errors for solid precipitation can reach 70% and higher in northern regions under windy conditions (Golubev 1969; Goodison 1978; Groisman and Easterling 1994; Goodison et al. 1998). At the same time, river discharge is believed to be one of the most accurately measured components of the hydrological cycle (Dingman 2001; Vörösmarty et al. 2001), integrating drainage basin behavior over a range of scales. River discharge is thus one of the most important monitoring tools for understanding the water cycle and the observed data has generally higher quality than observations of other major water balance components. Shiklomanov et al. (2006) evaluated the accuracy of river discharge observations for large Russian rivers flowing into the Arctic Ocean. They found that mean relative errors of daily discharge varied from less than 3% during the summer months (Pechora at UstTsilma, Ob at Salekhard) to more than 40% during ice-affected periods (Kolyma at Srednekolymsk). However the errors of monthly and annual discharge estimates are greatly reduced, as a result of aggregation and usually do not exceed 10% (Shiklomanov et al. 2006).

While there are large networks of observations available, there are several problems preventing a true Pan-Arctic picture from emerging. These include the following:

1. The density of monitoring stations is highly variable with a very sparse river gauge network in low populated areas.
2. During the 1990s, there was a significant net decline in monitoring sites in the Eurasian and North American Pan-Arctic (Figure 2 and Shiklomanov et al. 2002);
3. Delay in official data reporting from one to several years and restricted access to the Eurasian Pan-Arctic data;
4. Significant uncertainty of discharge estimates where available in near real time.

In the United States, the U.S. Geological Survey (USGS) is the primary agency that monitors streamflow; although many stream gauges are funded through partnerships with other federal, state, and local agencies. The USGS currently operates more than 120 stream gauges in Alaska and this number has

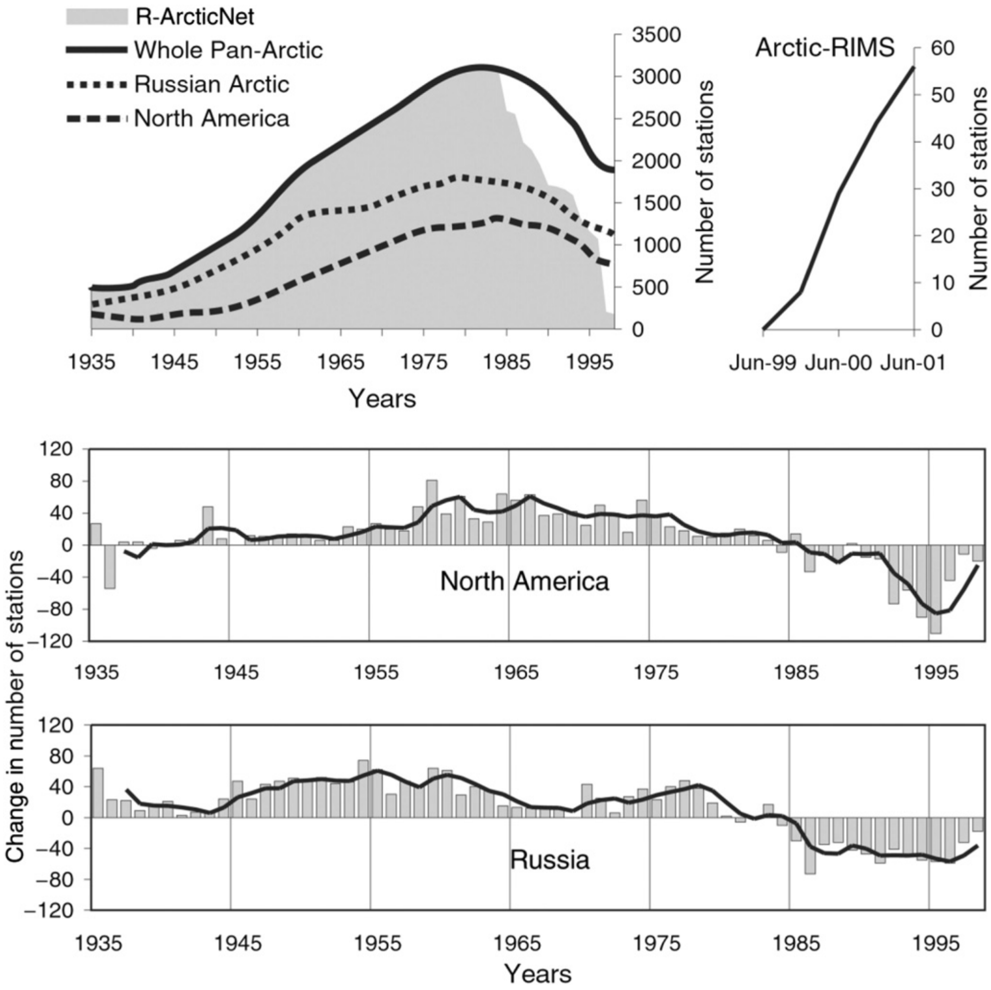

Figure 2 Dynamics of the river gauges in the Pan-Arctic drainage basin and data available in total R-ArcticNet, the operational Arctic-RIMS project, and changes in the number of river discharge gauges in North America and Russia are shown. In 1999, the discharge monitoring network had the same number of gauges as in 1960. Source: Shiklomanov, A. I., R. B. Lammers, C. J. Vorosmarty, 2002: Widespread decline in hydrological monitoring threatens Pan-Arctic research. *EOS Trans. Am. Geophys. Union*, **83,** 13–17.

been relatively stable during the last 20 years; however, currently fewer than 20 are funded through the National Streamflow Information Program (NSIP) of the USGS and the rest rely on funding partners.

In Canada, the majority of climate, hydrometric, and water quality stations are located in the southern half of the country, where the population and economic pressures are greatest. As a result, the adequacy of the network to describe hydrological and climatological characteristics, both spatially and temporally, decreases significantly in the northern part of the country and is particularly poor in the Canadian Arctic Archipelago. There is relatively good information on flows from large rivers (e.g., the Mackenzie and Nelson rivers). However, there is large uncertainty associated with the estimates of ungauged streamflow to the Arctic Ocean, largely due to the paucity of monitoring (Arctic-HYDRA 2010).

The discharge to the Arctic Ocean from Eurasia is better monitored than from North America as most of the river inflow is delivered through a small number of very large rivers with a long history of operating downstream gauges. Only 10 hydrological gauges are sufficient to capture 80% of the total Arctic Ocean drainage area in Russia. Hydrometric observations on small- and medium-sized rivers in the Russian Arctic are sparse and ungauged or poorly monitored areas dominate many parts of the region. Over the last 10 years, the accessibility of river discharge data for the Pan-Arctic has been significantly expanded by the release of the University of New Hampshire's R-ArcticNet database (http://www.R-ArcticNet.sr.unh.edu). However, sharp declines in Russian hydrometric gauging networks in the 1990s and delays in data reporting hamper research progress (Shiklomanov et al. 2002). Since 2000, governmental funding of Russian monitoring networks has improved, and as a result, the number of operating gauges has stabilized or even slightly increased. There are still significant delays in the timely delivery of Russian hydrological data to the international research community and the Arctic Rapid Monitoring System for the Pan-Arctic (Arctic-RIMS, http://rims.unh.edu/) was developed to facilitate and accelerate data reporting for the most important Russian river gauges.

Patterns in the reported decline of monitoring have recently been analyzed to see how they compare with the geographical

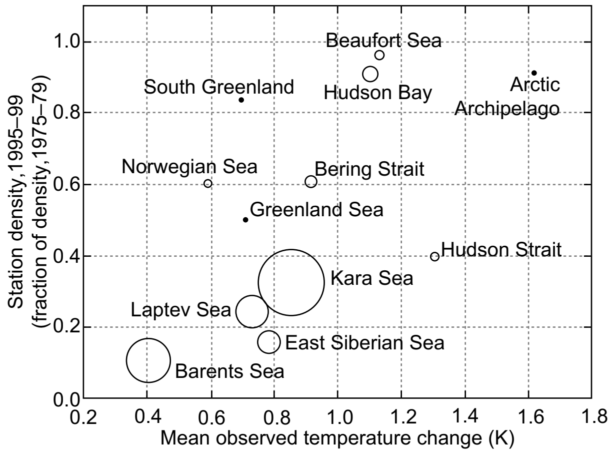

Figure 3 Change in density of hydrological stations in relation to observed temperature changes. Circle sizes correspond to the absolute number of closed stations. Adapted from: Bring, A., and G. Destouni, 2009: Hydrological and hydrochemical observation status in the Pan-Arctic drainage basin. *Polar Res.*, **28**, 327–338.

distribution of observed and predicted Arctic-wide climate. Figure 3 shows how station density has changed since the 1970s, in relation to observed temperature change (Bring and Destouni 2009). The vertical axis is the fraction of stations with accessible data for 1995–99, as a proportion of the stations with accessible data for 1975–79. A fraction of 1 means that the station density is the same today and a fraction of 0.2, for example, means that only 20% of the stations operational in the 1970s still provided data in the 1990s. The horizontal axis shows the mean observed temperature increase during 1995–2002, relative to the 1961–90 average. It is evident that the decline in network density has been greatest for four Eurasian basins. For the Kara Sea drainage, data from 520 stations is no longer available.

Sparse monitoring networks in the northern remote regions are experiencing the most dramatic changes in both climate and land cover. This is precisely the area where there is the most significant gap in existing ground observation networks.

5.11.3 River Streamflow

5.11.3.1 Annual Discharge Variability

There are numerous estimates of the river inflow into the entire Arctic Ocean based on different methods and drainage area calculations. Prowse and Flegg (2000) found the dominant source of variation was drainage area. They compared different geographical definitions of contributing land area to the Arctic Ocean ranging from 13×10^6 km^2 to 24×10^6 km^2 with most of the differences found in how various research groups tended to define the drainage system in North America. They found that river discharge scaled linearly, suggesting comparisons can be made between macroscale geographically varied studies using area normalized runoff.

Observational river data were extensively used to evaluate discharge from the various monitored areas to the Arctic Ocean (Shiklomanov et al. 2000; Peterson et al. 2002; Déry et al. 2005, 2009, 2011). These estimates, however, do not provide information for river discharge to the ocean from extensive unmonitored areas in North America and Eurasia, which are important to understanding the variability of regional runoff and Arctic Ocean freshwater balance (ACIA 2005). There are several different approaches to estimate the runoff from unmonitored areas. In our estimates of river flux to the ocean from the entire drainage area, we applied a combination of the hydrology analogy method (Shiklomanov and Shiklomanov 2003) and runoff simulated from meteorological data using the UNH water balance–water transport model (WBMPlus; Wisser et al. 2008, 2010). The first approach gives good results only if there are monitored river basins representative for regional hydrological, climatic, and land cover conditions. In this case, the runoff data for these rivers can be expanded to the unmonitored territory with similar conditions of runoff formation. Four largest rivers, Yenisey, Lena, Ob, and Mackenzie, contribute about 63% of total gauged discharge (Figure 4).

Unfortunately, in some regions (e.g., Canada's Arctic Archipelago) there are no gauges with regular observations, which could be used as analogs. For these areas we used the hydrological model (WBMPlus) driven with gridded meteorological data (Willmott and Matsuura 2009; Nickl et al. 2010) to estimate the river runoff from the unmonitored area. The simulated runoff was verified and adjusted with observations, if any observational data were available. Estimated river flux to the Arctic Ocean from the entire drainage area ($\sim 19 \times 10^6$ km^2) is approximately 4300 km^3 year^{-1} of which about 2900 km^3 year^{-1} originates from the $\sim 13.0 \times 10^6$ km^2 monitored Arctic land mass. Figure 5 demonstrates annual anomalies of total river flux to the Arctic Ocean from different continents over 1936–2004. The significant increase in river discharge to the Arctic Ocean with a rate of 3.9 km^3 year^{-1} is due to the increased discharge from the Asian (2.2 km^3 year^{-1}) and Northern American (1.2 km^3 year^{-1}) parts of the Arctic drainage basin. River inflow to the ocean from Asia is much better monitored ($\sim$84%) than from other continents. Therefore, uncertainties in estimates of total discharge to the ocean from Asia are much less than from the Europe and Northern America, where unmonitored areas occupy 30% and 65% of total drainage basin respectively (Figure 5).

The Hudson Bay drainage is the only Pan-Arctic sub-continental area where, according to our estimate, the river runoff shows decreasing trends over 1936–2004. Analysis of observational data for 42 rivers flowing into Hudson Bay over 1964–2000 showed a significant reduction of annual discharge equal to 96 km^3 year^{-1} over 37 years (Déry et al. 2005). However, analysis of newer, longer records of discharge to Hudson Bay over 1964–2008 showed no detectable trend with a slightly positive slope of 0.31 km^3 year^{-1} (Déry et al. 2011). The five year running mean in total Hudson Bay streamflow reveals two distinct periods marked by opposite trends. During the first 20 years, mean annual discharge into Hudson Bay decreases, whereas for the most recent 20 years, Hudson Bay streamflow increases sharply (Figure 6).

Eurasia contributes about 75% of the total terrestrial runoff to the Arctic Ocean (Shiklomanov and Shiklomanov 2003) and contains three of the four major Arctic rivers. Observations of combined river discharge from the six largest Russian north flowing rivers (N. Dvina, Pechora, Ob, Yenisey, Lena, and Kolyma) have shown an increase of 7% over the period 1936–99 (Peterson et al. 2002). More recent estimates have shown

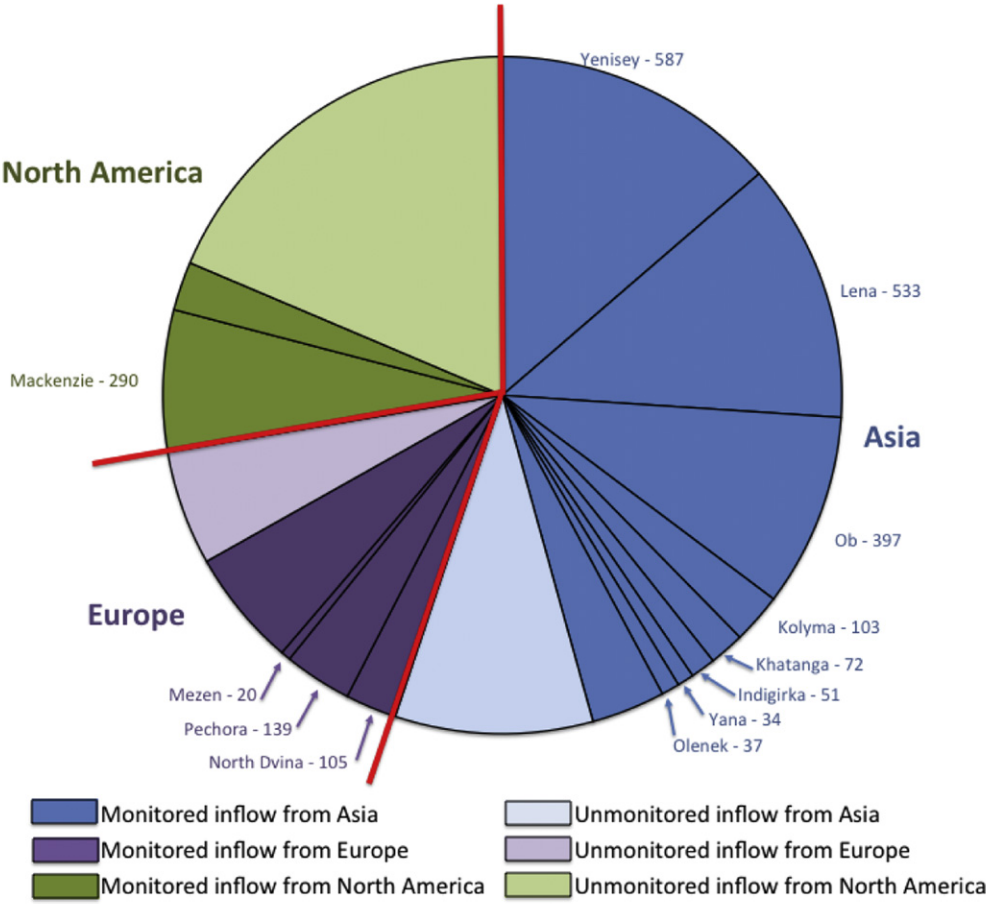

Figure 4 Surface river inflow into the Arctic Ocean from large rivers basins and continents. Source: Arctic-HYDRA, 2010: The Arctic Hydrological Cycle Monitoring? Modeling and Assessment Programme, Science and Implementation Plan. [Available online at http://arctichydra.arcticportal.org/images/stories/Arctic-HYDRA.pdf.] (accessed 21 December 2011).

this increase has continued into the twenty-first century (Richter-Menge 2009; Shiklomanov and Lammers 2009). The mean annual 2000–10 river discharge from the six largest Eurasian rivers was 186 km^3 (10%) higher than the long-term mean over 1936–99 (Figure 7).

Contemporary estimates of the river discharge showed a new historical maximum of the annual discharge to the Arctic Ocean from Eurasia in 2007 (Shiklomanov and Lammers 2009). An especially intensive increase in river discharge to the ocean from Eurasia was observed during the last 20 years, when sea ice extent in the Arctic Ocean has shown a progressive shrinkage (Stroeve et al. 2007). It is interesting to note that the correlation between Eurasian river discharge and sea ice extent over the period of 1979–2008 is $R = -0.72$, or greater than the correlation between runoff and observed precipitation fields aggregated across these Eurasian river basins ($R = 0.54$) (Shiklomanov and Lammers 2009). This suggests that both river runoff and sea ice were responding simultaneously to changes in large-scale hemispheric climate patterns.

There is also an increasing tendency in river discharge to the Arctic Ocean from North America. Figure 7 shows variability of total annual discharge for the four largest North American monitored rivers flowing into Arctic Ocean (Mackenzie, Peel, and Back) and Bering Strait (Yukon) over 1970–2008. The length of discharge records for Arctic rivers in North America is much less than in Eurasia and the increasing trend is not significant. However, the mean annual discharge to the ocean over 2000–08 from these four large North American Arctic rivers was 6% (31 km^3) greater than the long-term mean from 1970–99.

The spatial distribution of runoff across the Pan-Arctic is highly heterogeneous (Figure 8).

The smallest values (less than 10 mm year^{-1}) are found in the steppe regions of West Siberia and Canadian Prairies and the highest values, exceeding 600 mm year^{-1}, can be seen in areas of (1) orographic influence; Norway, the mountainous southern regions of central and eastern Siberia, and along the Alaska Range in southern Alaska and (2) those regions receiving precipitation from cyclonic activity; the European part of the basin, Pacific seacoast of Alaska, and eastern Hudson Bay drainage in Quebec (Lammers et al. 2001). Low runoff semi-arid regions are seen in the southwestern Ob basin, the Selenga basin in northern Mongolia, and the western Canadian Arctic drainage of the Nelson River system. These basins tend to be dry, due to their position on the lee-side of large mountain ranges and their continental climates. The large-scale structure of the

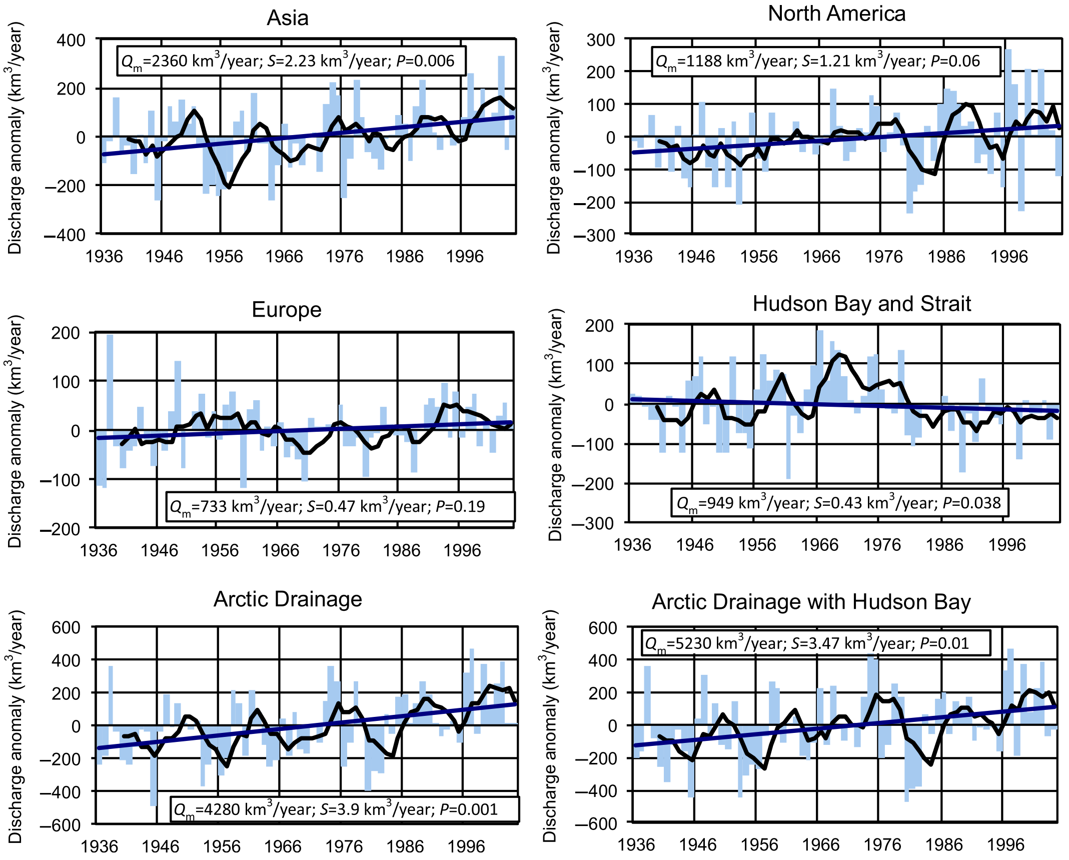

Figure 5 Anomalies of annual river discharge to the Arctic Ocean from different parts of the Pan-Arctic drainage basin over 1936–2004 (blue bars), 5-year moving average (thick black line), and linear trend (thick blue line). Long-term mean annual discharge (Q_m), slope of linear trend line (S), and p-value defining statistical significance of the trend line (P) (updated from Shiklomanov, I. A., A. I. Shiklomanov, R. B. Lammers, B. J. Peterson, and C. J. Vorosmarty, 2000: The dynamics of river water inflow to the Arctic Ocean. *The Freshwater Budget of the Arctic Ocean*, Lewis, E.L., et al., Eds., Kluwer Academic Publishers, the Netherlands, 281–296.).

runoff surface is consistent with the long-term runoff maps given by AARI (1985) and by Fisheries and Environment Canada (1978).

Analysis of discharge variability for the largest monitored individual river basins over the observational periods shows significant positive trends (5% significance level) for the Yenisey, Lena, Pechora, and Severnaya Dvina rivers and no trend for the Kolyma, Ob, Mackenzie, and Yukon rivers. However all large rivers show tendencies toward the increasing discharge (Figure 9). Higher rates of river discharge increases are seen during the period of most intensive air temperature rise (Hansen et al. 2010) over 1980–2008 when all rivers (except the Yukon) show accelerated trend lines (Figure 9). The mean annual discharge of the six Eurasian rivers for 1980–2008 was 100 km^3 or 6% higher than the discharge for the 1936–79 period. As a comparison, this is greater than the annual discharge of the entire Kolyma River, which is the fourth largest Russian north flowing basin.

5.11.3.2 Seasonal Discharge Variability

Knowledge of seasonal discharge variability and change is very important to better understand causes responsible for the dramatic increase in annual river discharge to the Arctic Ocean.

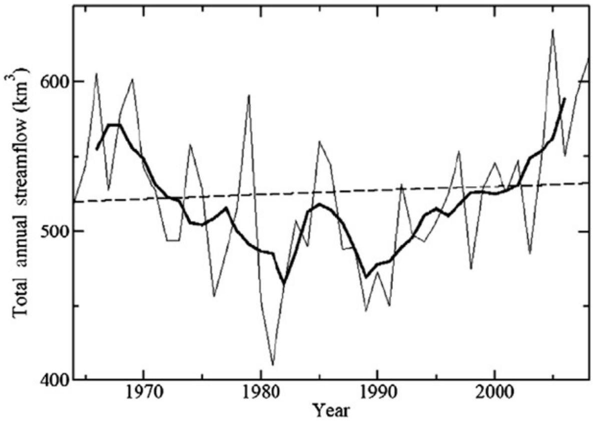

Figure 6 Total annual streamflow into Hudson Bay, 1964–2008 (thin line). A five year running mean (thick line) is shown and the linear trend assessed with Kendall–Theil Robust Line shown for the overall 45-year period (dashed line). Source: Déry, S. J., T. J. Mlynowski, M. A. Hernández-Henríquez, and F. Straneo, 2011: Interannual variability and interdecadal trends in Hudson Bay streamflow. *J. Mar. Syst.*, **88,** 341–351.

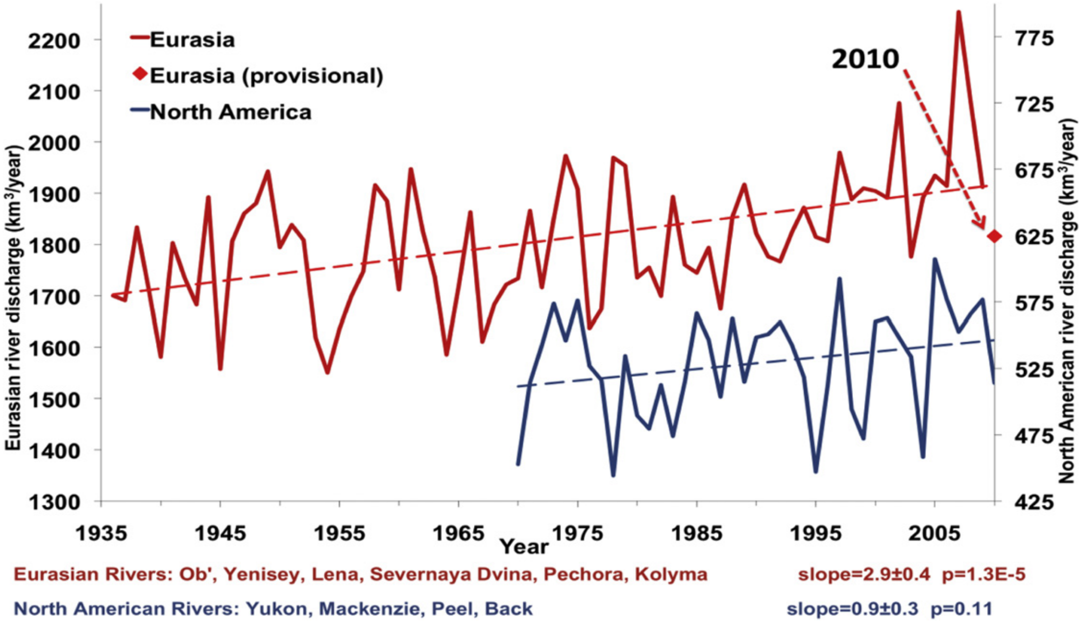

Figure 7 Total annual river discharge to the Arctic Ocean from the six largest rivers in the Eurasian Arctic for the observational period 1936–2010 (updated from Peterson, B. J., R. M. Holmes, J. W. McClelland, C. J. Vorosmarty, R. B. Lammers, A. I. Shiklomanov, I. A. Shiklomanov, and S. Rahmstorf, 2002: Increasing river discharge to the Arctic Ocean. *Science*, **298**, 2171–2173, 13 December 2002.) (red line) and from the four large North American Pan-Arctic rivers over 1970–2010 (blue line). The least squares linear trend lines are shown as dashed lines.

In addition to climate-induced river streamflow variations, water management such as construction of large reservoirs, inter-basin water diversions, and water withdrawals for various needs can significantly impact river discharge variability (Shiklomanov and Lammers 2009; Ye et al. 2003; Yang et al. 2004; Vörösmarty et al. 1997). However, human influence on the hydrological regime of Pan-Arctic rivers is usually considered to be minor in comparison with mid to low latitude rivers, due to lower population, severe natural conditions, and scarce development (Vörösmarty et al. 1997; Lammers et al. 2001). Water consumption for human needs in large Pan-Arctic River basins do not exceed 1–1.5% of total river discharge and do not significantly affect annual variability of river discharge to the Arctic Ocean (Shiklomanov and Shiklomanov 2003). At the same time, engineered control of streamflow as the result of reservoir regulation is very important for many large Arctic rivers. The construction of dams and reservoirs in river systems has the effect of changing the timing of river flow. At higher latitudes, the impoundments are primarily used for hydroelectric power generation and storing water for dryer summer seasons. Thus, they redistribute water between the seasons and can significantly change the seasonal hydrological regime reducing peak discharge during spring and early summer and increasing discharge during low-flow periods. This effect on seasonal hydrology is widely documented for the Ob, Yenisey, Lena, and Mackenzie rivers (Ye et al. 2003; Shiklomanov and Lammers 2009; Berezovskaya et al. 2005; Adam et al. 2007). The results for these basins demonstrate that reservoir effects can exceed climate-induced hydrological changes even in downstream gauges remotely located from reservoirs. In addition to seasonal discharge distribution, large dams may also affect yearly flow characteristics at the basin scale, particularly during reservoir filling periods immediately after dam construction (Stuefer et al. 2011; Yang et al. 2004; Shiklomanov and Lammers 2009). Thus, to analyze the climate-induced long-term variability of seasonal discharge to the Arctic Ocean associated with climate and to better understand the physical mechanisms driving the observed changes in seasonal discharge, it is necessary to eliminate the direct human impact from the observed streamflow records.

We developed Hydrograph Transformation Model (Shiklomanov et al. 2011) to eliminate reservoir effects from observational hydrographic data and applied it to the three largest Pan-Arctic River basins – Yenisey, Lena, and Ob. The linear model with concentrated parameters is based on routing of daily discharge hydrographs from the unregulated part of the basin along the river network to the downstream river gauge. The optimal parameters for the model are evaluated from the minimization of mean square deviation between the observed and simulated daily discharge values over the pre-dam period. The model has shown less than 10% mean relative errors of modeled daily discharge from observations over the pre-dam period, which are comparable to the accuracy of daily discharge observations on large Siberian rivers (Shiklomanov et al. 2006) (Figure 10, left panel). Simulations of natural streamflow regime during the post-dam period are made consequently from upstream to downstream using the routing parameters defined over the pre-dam period. The effect of reservoirs on river discharge can be seen clearly at the river gauge on the Yenisey River at Bazaikha, where the strong spring snowmelt pulse has been completely eliminated (Figure 10, right panel) by the construction of the massive Krasnoyarsk dam and reservoir on the main stem of the Yenisey River (Shiklomanov and Lammers 2009). With the additional flow of multiple large tributaries into the Yenisey River, these severe effects are attenuated downstream and once the last downstream gauge (Igarka) is reached the overall effect of impoundments is significantly decreased.

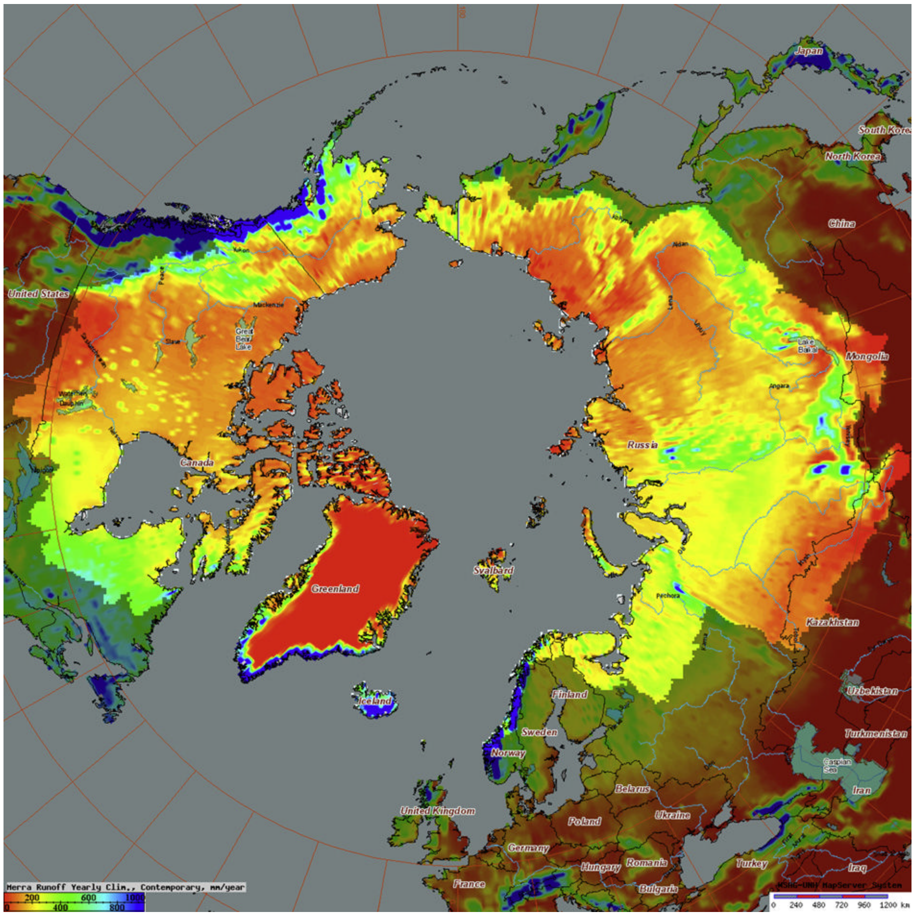
Japan
South Korea
North Korea
China
Mongolia
Lake Baikal
Angara
Aldan
Russia
Pechora
Kazakhstan
Uzbekistan
Turkmenistan
Caspian Sea
Iran
Iraq
Turkey
Ukraine
Belarus
Poland
Romania
Bulgaria
Hungary
Germany
France
United Kingdom
Norway
Sweden
Finland
Svalbard
Iceland
Greenland
Canada
United States
Yukon
Mackenzie
Great Bear Lake
Slave
Merra Runoff Yearly Clim., Contemporary, mm/year
0
200
400
600
800
1000
WSAG-UNH MapServer System
0 240 480 720 960 1200 km

Figure 8 Long-term average annual gridded runoff surface climatology (January 1979 – December 2011) is highlighted for the Pan-Arctic. Map based on runoff simulations of UNH water balance model (WBMPlus) (Wisser, D., B. M. Fekete, C. J. Vörösmarty, and A. H. Schumann, 2010: Recon-structing 20th century global hydrography: a contribution to the Global Terrestrial Network- Hydrology (GTN-H). *Hydrol. Earth Syst. Sci.*, **14**, 1–24.) driven with NASA Modern Era Retrospective analysis for Research and Applications (MERRA) re-analysis (Rienecker, M. M. and Coauthors, 2011: MERRA – NASA's Modern-Era Retrospective Analysis for Research and Applications. *J. Clim.*, **24**, 3624–3648, http://dx.doi.org/10.1175/JCLI-D-11-00015.1.). The MERRA driven runoff simulation has a good agreement with high latitudes observational discharge (Shiklomanov et al. 2011).

Analysis of annual and seasonal observed and naturalized (modeled) river discharge for downstream river gauges showed that at annual time steps the trends are less impacted by dam construction, whereas seasonal discharge variability is strongly confounded by both climate variability, human impact, and the climate signals are often overwhelmed by the human-induced disturbances in river discharge.

Combined analysis of observed and naturalized discharge for the six largest Eurasian Pan-Arctic rivers (Kolyma, Yenisey, Lena, Ob, Severnaya Dvina, and Pechora) showed that there is a significant difference in seasonal discharge trends estimated from observed and naturalized data. Based on observations the annual discharge increase is mostly due to an increase of winter (~70%) and spring flows (~25%). Naturalized discharge records show similar trends in annual discharge accompanied with streamflow increases in spring (account for 49%), winter (account for 31%), and summer-fall (account for 20%) (Figure 11).

Similar results for changes in seasonal discharge across the Eurasian Pan-Arctic were obtained based on river flow data for small- and medium- sized rivers. Shiklomanov (2008) analyzed monthly discharge records longer than 50 years from 75 gauges in the Russian Pan-Arctic. The analysis considered only those rivers for which there has been no significant human impact on the hydrological regime. The mean seasonal discharge over the period 1978–2005 was compared with mean discharge over the period 1946–77 (Figure 12). A prevailing pattern of year-round discharge increases across most of Northern and Eastern Siberia, and winter increases across the entire Russian Pan-Arctic was found (Figure 12(a)). Winter runoff has increased by as much as 40–60% in the Irtysh basin, a tributary of the Ob in South-eastern Siberia, and by as much as 15–35% in Northern Siberia. Additionally, significant increases were found in summer-fall runoff in the Irtysh and Tobol basins (25–40%) and in Eastern Siberia (10–25%) (Figure 12(c)). Spring runoff also demonstrates an increase with the most significant values in Western and Eastern Siberia (Figure 12(b)).

Thus, seasonal discharge records aggregated for large river basins and small–medium sized watersheds show similar tendencies over the long-term period. All seasons contributed to the increase in annual discharge to the Arctic Ocean and it likely results from multiple causes. The increase in volume of spring

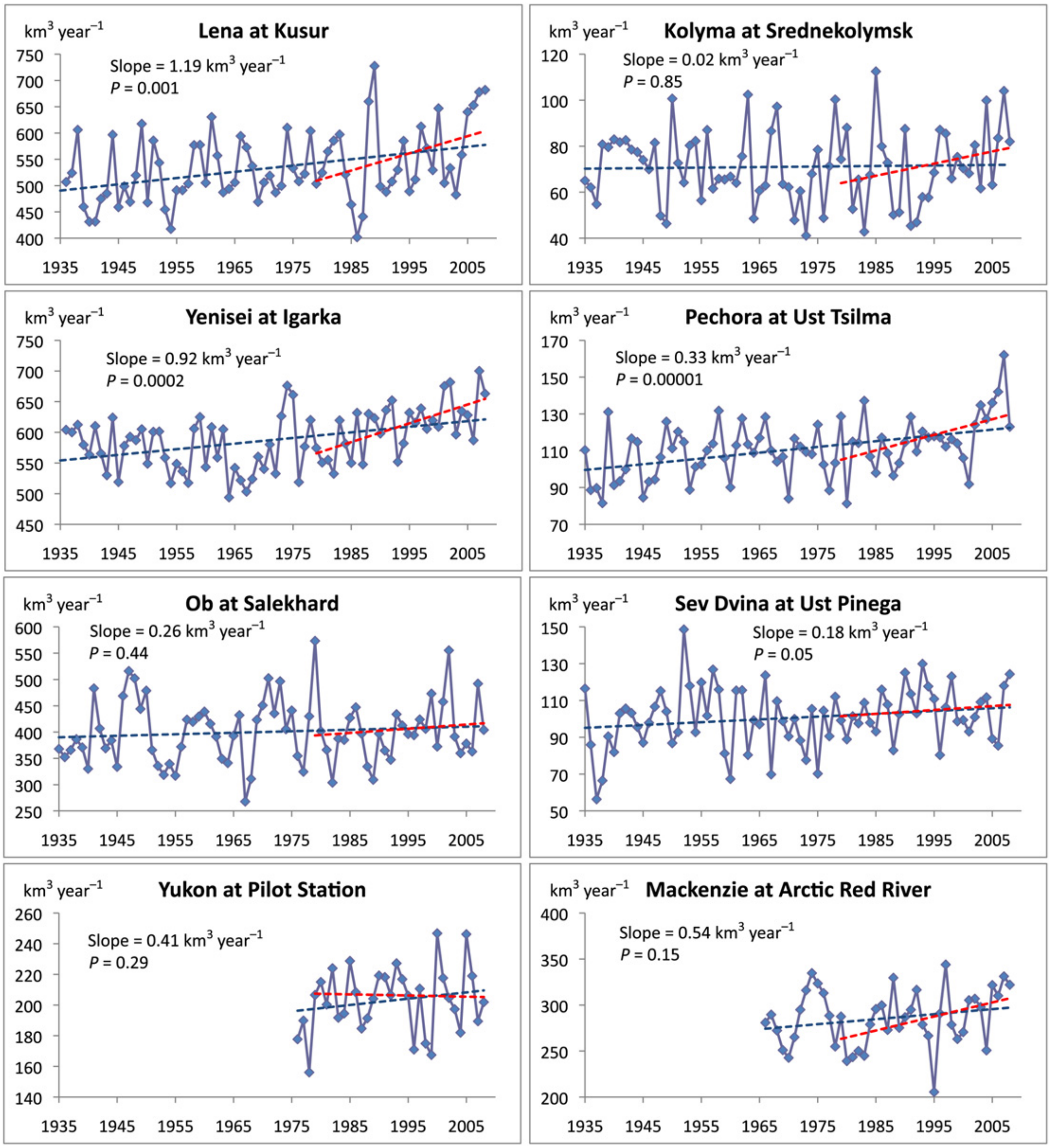

Figure 9 Annual discharge variations for the eight largest monitored Pan-Arctic rivers over the periods of observations. Dashed lines show linear trends for entire observational periods (blue) and for 1980–2008 (red). Updated historical data from the R-ArcticNet river discharge archive (http://www.R-ArcticNet.sr.unh.edu) were used for the graphs. Some gaps in the discharge records were reconstructed using information from upstream gauges.

discharge is supported by increases in cold season precipitation reported in several publications (Rawlins et al. 2006, 2010). The rise of winter, summer, and fall runoff is probably related with mobilization of subsurface water activity due to permafrost thawing, decreased winter freezing of soils and winter snowmelt events caused by warmer winters and deeper snowpack (Smith et al. 2007). A more deeply thawed, or more frequently thawed, landscape would not only accept more infiltration from the surface, but also shift water storage from the surface–near-surface to greater depths, reducing evapotranspiration water losses to the atmosphere (Smith et al. 2007).

Changes in precipitation are usually considered as the primary cause of any alteration to the hydrological regime and this is often the default assumption (McClelland et al. 2004). A comprehensive analysis of precipitation and river runoff was subsequently carried out using several long-term precipitation data sets (Rawlins et al. 2006; Shiklomanov et al. 2007) and river discharge from R-ArcticNet (Lammers et al. 2001; Shiklomanov and Lammers 2009). Annual snowfall across the Eurasian Pan-Arctic exhibited a strong significant increase from 1936 to the late 1950s and a moderately significant decrease thereafter. Due to spatial variation, an integrated signal across northern drainage basins yielded no significant change in annual precipitation. Berezovskaya et al. (2004) suggested that either the existing precipitation products were unable to capture high-latitude precipitation changes, or some other processes were responsible. Summer-fall precipitation, which controls soil and groundwater storage before freeze over,

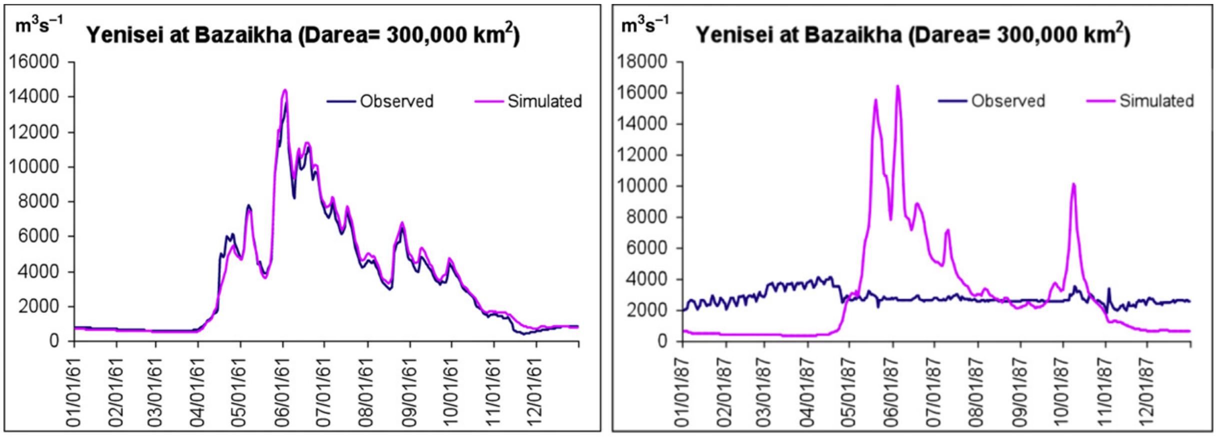

Figure 10 Daily observed and simulated discharge hydrographs for the gauge at Bazaikha on the Yenisey River. The left panel shows a pre-dam year and demonstrates the accuracy of the simulations. The right panel shows the effects of dam regulation at this gauge. Shiklomanov, A. I., and R. B. Lammers, 2009: Record Russian river discharge in 2007 and the limits of analysis. *Environ. Res. Lett.*, **4** (045015). 9 pp, http://dx.doi.org/10.1088/1748–9326/4/4/045015.

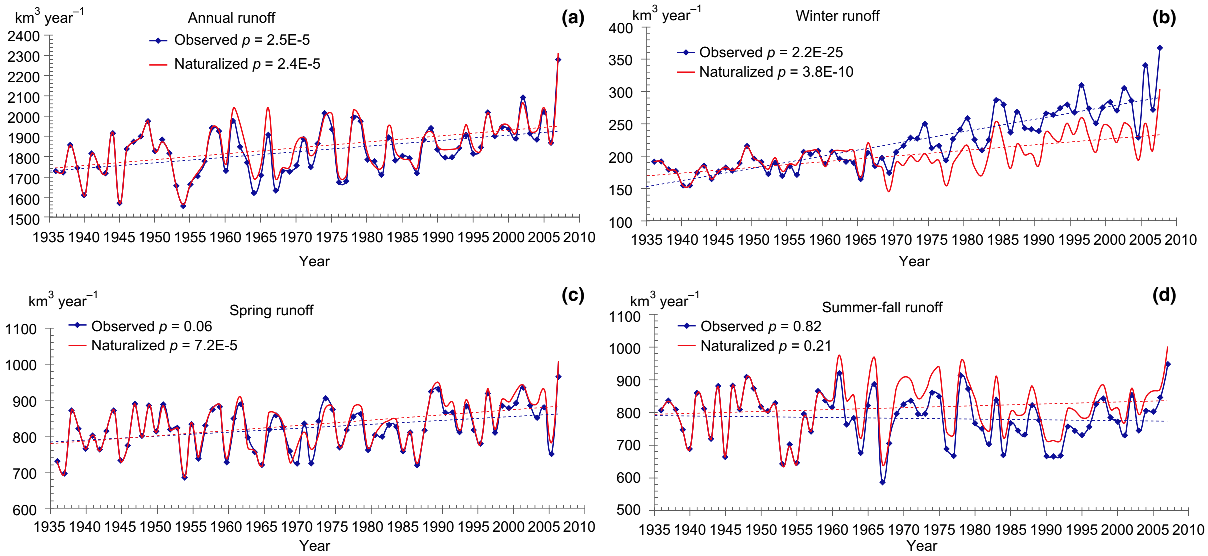

Figure 11 Annual and seasonal river discharge for six largest Eurasian rivers flowing to the Arctic Ocean (Yenisey, Lena, Ob, Kolyma, Pechora, and Severnaya Dvina) over 1936–2010. Observed discharge is shown with blue lines and naturalized (without water management impact) is shown with red lines. Source: Shiklomanov, A. I., and R. B. Lammers, 2009: Record Russian river discharge in 2007 and the limits of analysis, *Environ. Res. Lett.*, **4,** 045015, 9, http://dx.doi.org/10.1088/1748–9326/4/4/045015.

showed declines (Rawlins et al. 2006; Berezovskaya et al. 2004) and presents an offsetting trend to the well-documented increases in fall–winter runoff.

In contrast to precipitation, the significant increase in air temperature across the North Eurasian Pan-Arctic has been widely and consistently documented (e.g., Hansen et al. 2010) and it is expected to continue with higher rates in future (ACIA 2005). The warming of the Pan-Arctic has already led to significant changes in land cover (Gutman and Reissell 2010). Thawing of permafrost (Brown and Romanovsky 2008), changing soil freeze–thaw cycle (McDonald et al. 2004), reductions and disappearance of wetland–natural lake areas (Smith et al. 2005), thinning river ice and glacier retreat (ACIA 2005), as well as, changes in vegetation structure (Zhou et al. 2003) may have significant impacts upon the hydrological regime and river discharge even without noticeable changes in precipitation.

5.11.3.3 Extreme Discharge Variability

Maximum river discharge often results in flooding. Future climate model projections suggest that the frequency and magnitude of extreme hydrological events, including floods, would increase at high latitudes in response to climate change (IPCC 2007). Shiklomanov et al. (2007) analyzed long-term variability in maximum daily spring discharge for 139 small- and medium-

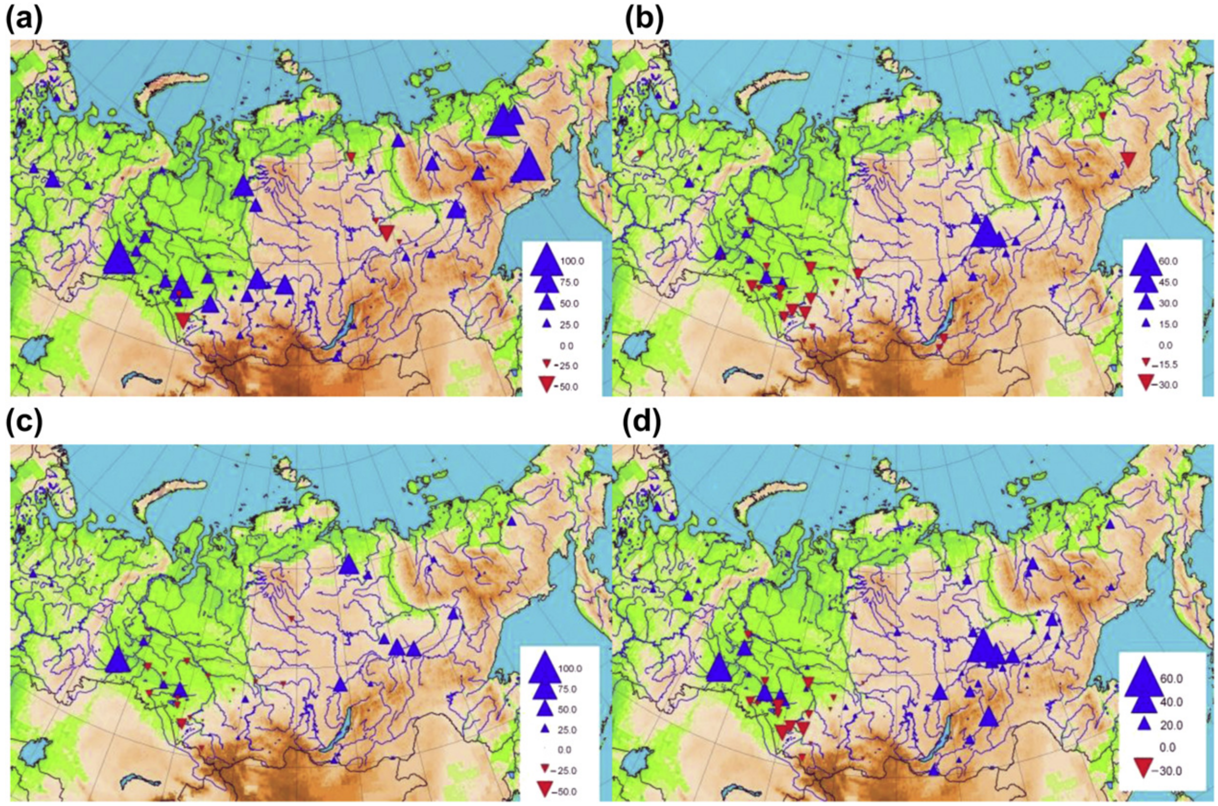

Figure 12 Anomalies of winter (a), spring (b), summer-fall (c), and annual (d) runoff across the Russian Arctic Ocean drainage basin for 1978–2005 (in % relative to 1946–77). Source: Shiklomanov I. A., Ed., 2008: *Water Resources of Russia and Their Use*. Nauka, St. Petersburg, 598 pp. (in Russian).

sized Russian rivers (16–50 000 km^2) with minimal human impact. Trend analyses were applied to the magnitude and timing of maximum spring discharge values over the periods 1960–2001, 1950–2001, 1940–2001, and 1930–2001 using both least squares linear regression and the more robust, nonparametric Mann–Kendall test (Helsel and Hirsch 1992). All rivers had clearly pronounced spring peaks in April–June.

Relative changes in spring maximum discharge for different periods are shown in Figure 13. There are approximately the same number of gauges with both positive and negative changes for all time periods. The number of gauges, with significant positive and negative trends, are similar for 1960–2001 and 1930–2001, and there are slightly more gauges with significant negative trends for 1950–2001 and 1940–2001. Overall, we find no widespread significant changes in trends of spring maximum discharge across the Russian Arctic drainage basin. However, there are several regions with common patterns in maximum discharge change. Significant decreasing tendencies are noted across the south of central siberia and far east (regions 2 and 4 in Figure 13). The change in spring maximum discharge in these regions coincides with trends in cold season precipitation, which mostly generates spring peak flow. The Lena River basin and North European Russia (regions 1 and 3 Figure 13) showed significant increases in maximum discharge. There was no uniformity between changes in precipitation over the cold period and maximum discharge. This discrepancy leads us to suspect that other factors were responsible for discharge changes across these regions.

Maximum river discharge is usually associated with floods, which cause more damage in Russia than any other natural disaster. We recognize, however, that maximum water level, which results in out of bank flow does not always conjoin with maximum discharge, owing to the backwater effects and ice damming in rivers. Recent estimates of extreme water levels, to characterize the flood situation across Russia, showed the greatest increase in water level peaks in south central siberia and the far east (Shiklomanov 2008) where spring peak discharge is decreasing (Shiklomanov et al. 2007). About 50% of river gauges in these regions showed 10–75% increase in maximum water level over 1981–2005, but the ice damming was a main cause of extreme floods.

Minimum discharge is an important characteristic of water availability. Due to the extreme seasonality, Arctic runoff is highly variable throughout the year and inspite of relatively high annual runoff many rivers in high latitudes can dry out or freeze over during certain periods creating difficulties for water supply. The minimum discharge is most sensitive to groundwater and/or unsaturated zone water inputs and its volume characterizes changes in subsurface water contributions to the river. Smith et al. (2007) analyzed the same Russian time series as Shiklomanov et al. (2007), discussed above, to examine daily discharge minima. They found that the increases in minimum daily discharge were more abundant than the decreases, leading

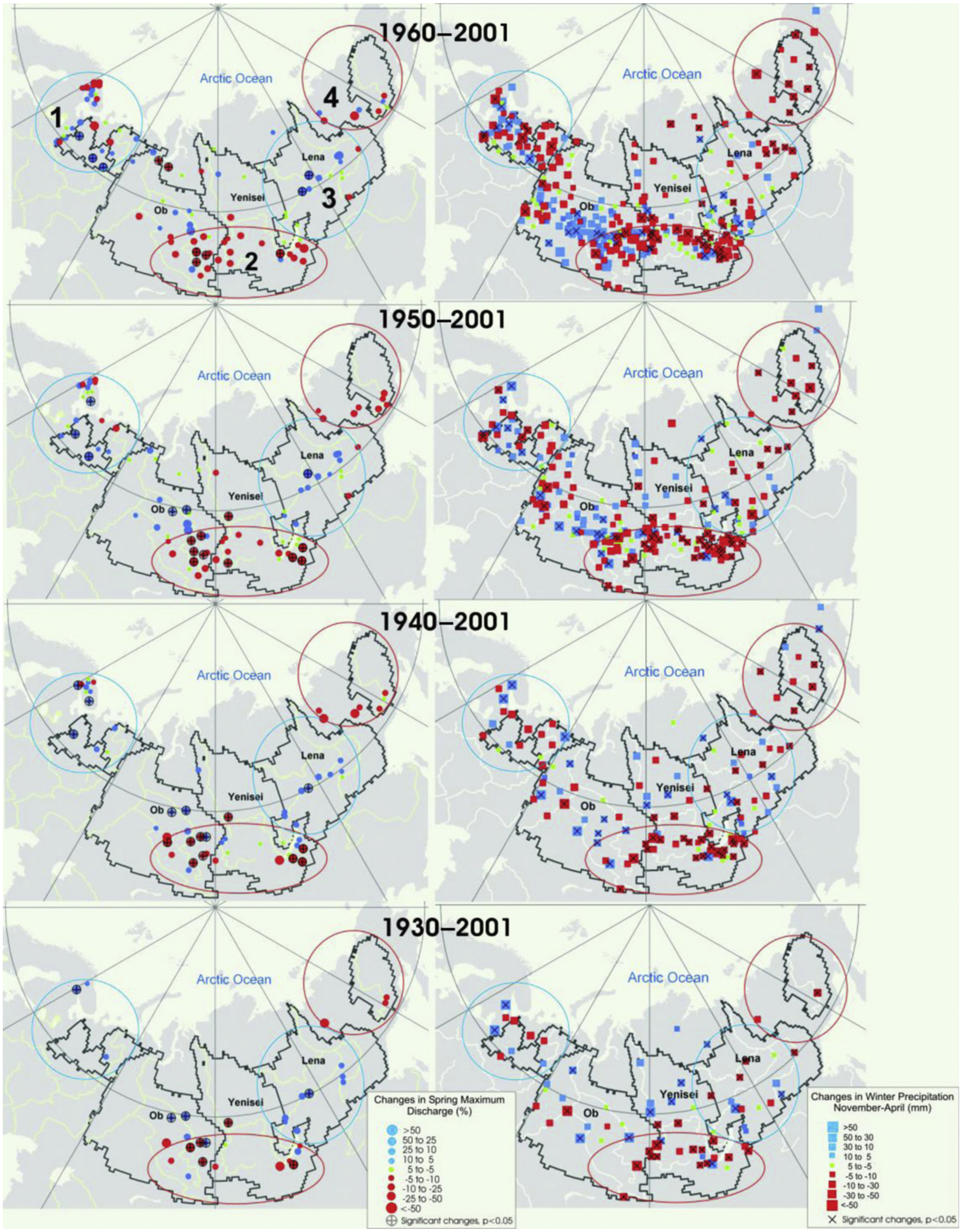
1960–2001
1950–2001
1940–2001
1930–2001
Arctic Ocean
Ob
Yenisei
Lena
1
2
3
4
Changes in Spring Maximum Discharge (%)
>50
50 to 25
25 to 10
10 to 5
5 to -5
-5 to -10
-10 to -25
-25 to -50
<-50
Significant changes, p<0.05
Changes in Winter Precipitation November-April (mm)
>50
50 to 30
30 to 10
10 to 5
5 to -5
-5 to -10
-10 to -30
-30 to -50
<-50
Significant changes, p<0.05

Figure 13 Relative changes in spring daily maximum discharge (%) (right panel) and changes in precipitation over cold period (November to April, in millimeters) (left panel). Blue circles and squares represent positive trends, red represents negative trends, and green marks gauges with no change (less than ±5%). Crosses highlight stations with significant trends ($p < 0.05$). Ovals encircle regions where analysis of aggregated changes has been made. Colors of ovals reflect positive (blue) or negative (red) changes over the given periods. The region identification numbers discussed in the text are shown in the top left plot. Source: Shiklomanov, A. I., R. B. Lammers, M. A. Rawlins, L. C. Smith, and T. M. Pavelsky, 2007: Temporal and spatial variations in maximum river discharge from a new Russian data set. *J. Geophys. Res. Biogeosci.*, **112**, G04S53, http://dx.doi.org/10.1029/2006JG000352.

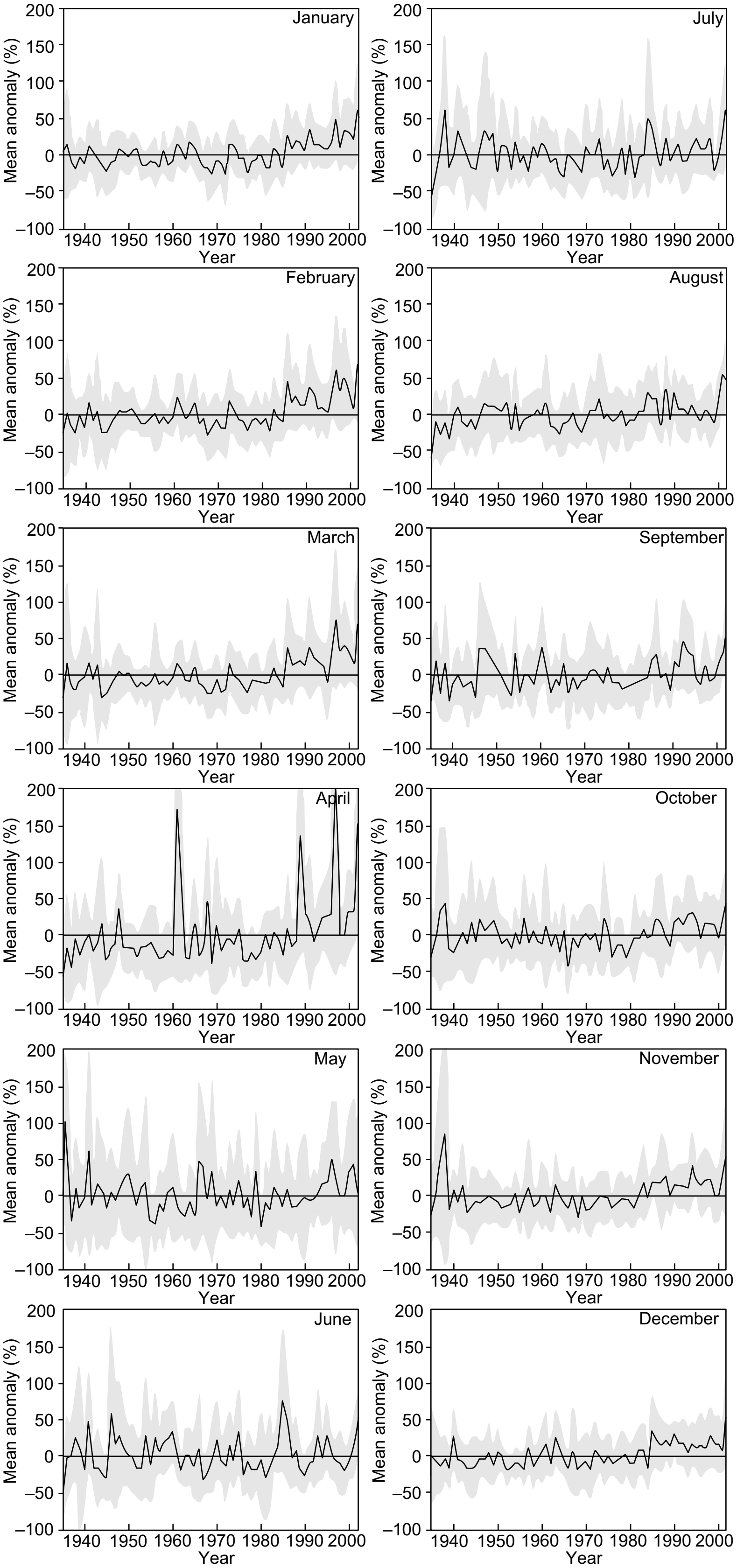

Figure 14 Monthly anomalies in minimum daily discharge expressed as a percent of mean minimum daily discharge and averaged for 12 stations with predominantly complete records, 1935–2002. Substantial positive anomalies since ~1985 in November through March suggest unprecedented recent increases in winter minimum flows for this subset of stations. Source: Smith, L. C., T. M. Pavelsky, G. M. MacDonald, A. I. Shiklomanov, and R. B. Lammers, 2007: Rising minimum daily flows in northern Eurasian rivers suggest a growing influence of groundwater in the high-latitude water cycle. *J. Geophys. Res. Biogeosci.*, **112,** G04S47, http://dx.doi.org/10.1029/2006JG000327.

them to suggest this as sole factor contributing to the overall rise in Russian river discharge to the Arctic Ocean. There was no coherent spatial pattern to these increases. However, Smith et al. (2007) acknowledged these increases in later years in minimum flow involved a small number of gauges ($n \leq 10$) with a very different spatial distribution of gauges than the other time periods. As a result, they tested the hypothesis of accelerating Arctic hydroclimatology by selecting a small subset of data with very long records covering the period 1935–2002. They looked at monthly anomalies in daily minimum discharge (**Figure 14**) and found increases in the long-term records from approximately 1985 onwards for the months November to April and for all months since 2000. Additionally, during the last few years of the time series, 9 of 12 months showed magnitudes at or near record levels (**Figure 14**). Overall, they found no unique role for permafrost contributions to minimum daily flow, yet the observed signal does suggest a 'thawlike process'. This indicates a much more complicated set of interactions between climate, evapotranspiration, infiltration, thawing lakes, groundwater, and permafrost processes.

5.11.4 Discussion and Conclusions

The hydrological regime of Pan-Arctic rivers has undergone dramatic changes in the last few decades, but the causes responsible for these changes are not fully understood. River discharge as an integrated characteristic of numerous geophysical processes and as one of the most accurately measured components of water cycle is very important for tracking and understanding of environmental changes at high latitudes. However, despite the value of discharge information, ungauged or poorly monitored areas dominate many parts of the Pan-Arctic and recent declines in Russian and Canadian hydrometric station networks, and some restrictions and delays in the dissemination of data, especially for Russia, obstruct research progress. There is therefore a clear need to establish an integrated, international operational system for the monitoring of Pan-Arctic hydrology.

According to most contemporary assessments the total discharge to the Arctic Ocean is approximately 4300 km^3 $year^{-1}$ and continental contributions to the river input into the Arctic Ocean for Asia, North America, and Europe are 55%, 28%, and 17% respectively. Total river discharge to the Arctic Ocean has shown a significant increase over 1936–2004 with a mean linear slope of 3.9 km^3 $year^{-1}$ and all continents contribute to this increase. The Hudson Bay drainage basin is the only Pan-Arctic sub-continental area where according to our estimate the river discharge shows decreasing trends over 1936–2004. Discharge from the monitored part of the Pan-Arctic drainage is increasing even more intensively with an extremely significant increase of Eurasian river flow. The total increase in the discharge of six largest Eurasian rivers flowing to the Arctic Ocean (N. Dvina, Pechora, Ob, Yenisey, Lena, and Kolyma) over 1936–2010, computed based on linear trend, was approximately 210 km^3 or equivalent to the Yukon River discharge.

Using newly 'naturalized' (without local human impact) river discharge data for the great Siberian rivers, we found that this dramatic increase in annual discharge is the result of changes during all seasons and this assumes multiple causes of additional contributions to streamflow. Especially noticeable were relative increases in river discharge found during the winter period when high-latitude river runoff is minimal. Many rivers demonstrate more than 100% discharge increase in winter, pointing out the mobilization of subsurface water activity at high latitudes.

Thus, we conclude that the hydrological regime of rivers across the Pan-Arctic is strongly intensifying producing more and more freshwater input to the Arctic Ocean. Such changes in river flux, along with thawing of sea ice, and increasing precipitation over the ocean may exert significant control over the North Atlantic meridional overturning (thermohaline) circulation. This is significant for global ocean circulation by controlling the volume of North Atlantic deep water formation with potentially dramatic consequences for climate in the Northern Hemisphere. Accordingly, to project possible extreme anomalies and better adapt to ongoing and oncoming environmental changes we should expand our knowledge and understanding of these hydrological alterations.

To better understand the physical mechanisms driving the hydrological changes at high latitudes, it is necessary to (1) extend the regional experimental investigation on interactions between ground and surface water, especially in the permafrost and transition zones; (2) extend our *in situ* monitoring networks, especially in currently unmonitored rivers, and improve international collaboration in data exchange; (3) expand the scale of remote-sensing monitoring efforts; and (4) improve representation of physical processes at different scales in hydrological models. These four elements are interrelated and the best progress can be reached if development will simultaneously involve all these fundamental pieces.

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5.12 The Sustainability of Pacific Northwest Hydropower Generation in the Context of Nonstationarity and Renewable Energy Growth

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5.12.1 Introduction

For two millenia, water power has been an important energy resource in regions of the world that boast the requisite characteristic of ample streamflow coupled with sufficient hydraulic head (elevation gradient). One of the earliest applications provided energy for milling grain, using waterwheels driven by the weight of falling water (Greece, *c*.100 BC; cf. http://en.wikipedia.org/wiki/Water_wheel), a practice that spread to Europe and Asia as early as the first century AD. The earliest example of a turbine-like water mill implementation dates to third or fourth century AD at a site in modern day Tunisia. Along with the sail, use of water for milling is the earliest example of a machine harnessing natural forces to replace human labor.

The use of water wheels for power continued for the next 2000 years, but their size and weight limited the flow and head that could be converted into power. During the industrial revolution of the nineteenth century, these limitations were overcome by new materials, manufacturing capabilities, and scientific and engineering methods that ushered in a range of turbine designs to enable far larger projects. This technical development set the stage for rapid growth and expansion of the hydropower industry in the twentieth century, leading to a global installed capacity of 1000 GW of hydroelectricity as of 2010, or about 24% of the world's electricity.

Since the rise of the environmental movement in the 1970s, however, hydropower development in many first-world nations has largely ceased. Today, initiatives to remove old dams (including marginal hydropower facilities) have gained the following. Dam removals have been primarily motivated by interest in restoring watershed habitats to support fisheries and, in regions such as the US Pacific Northwest (PNW), the local cultural heritage associated with salmonids. Additional concerns over the outlook for hydropower are rooted in the

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findings of several decades of research characterizing the effects of low-frequency climate variability and possible future climate change on hydrology. North American midlatitude climate has warmed significantly in the past 30 years, leading to reduced snowpack, earlier runoff, and diminished spring and summer streamflows, as well as a possibility of greater extremes in flooding and drought. Although reservoir-based hydropower is designed to manage flow variability, hydroclimatic variability of this type undoubtedly has potential to impact hydropower generation and operations. The western US drought of the 2000s, for instance, substantially reduced Colorado River reservoir storage (Lakes Powell and Mead), leading to reductions in hydropower generation of up to 30%. Potential climatic change impacts and fears over energy security also spur concerns over the sustainability of thermal generation practices, driving interest in renewable energy development that includes, to some extent, hydropower.

The combination of potential climate-related impacts and continued environmental pressure on hydropower motivates this chapter, which assesses the sustainability of hydropower in the twenty-first century. The chapter has three major thematic parts. The first (see Section 5.12.2) describes the basic physics of hydropower, its range of implementation, and history of growth. The second part (see Sections 5.12.3 and 5.12.4) discusses challenges for hydropower, including environmental and social concerns, as well as the regulatory environment. The third part (see Sections 5.12.5 and 5.12.6) describes two issues that are potential drivers for change in the hydropower industry: the growth of renewable energy and nonstationarity. The term 'nonstationarity' is used here in the water resource engineering and management context described by Milly et al. (2008) – that is, reflecting concern that sample statistics describing weather and streamflow deduced from available historical records are not sufficient to capture true population statistics in light of various forms of low-frequency variability or longer term trends in system behavior. The chapter concludes with a discussion of the implications of the issues highlighted in earlier sections for the sustainability of hydropower. The PNW region of North America serves as the chapter's focus, but many of the factors discussed apply, in varying degrees, to hydropower elsewhere in the world.

5.12.2 Harnessing Hydropower: An Overview

5.12.2.1 Extracting Energy from Water

Modern hydropower plants are generally divided into storage projects, which have a reservoir large enough to detain or regulate runoff significantly, and *run-of-river* projects, which may have a weir and pondage (i.e., small storage relative to flow) but generally not an appreciable storage; thus they must pass inflows and cannot buffer their variability. Within these categories of projects, power generated by a wide range of devices and associated facility designs. A factor commonly used to discriminate between types of devices and projects is the amount of hydraulic head, or the water's potential energy, available, given the project location and design. The most productive, typically large reservoir projects often make use of medium- to high-head turbines, whereas many run-of-river projects use low- to medium-head turbines. In a reservoir project, as illustrated by the schematic of Figure 1, the hydraulic head is developed from the difference in the reservoir surface elevation and the project tailwater elevation.

Hydroelectric plants that extract energy both from the flow rate of the water and its pressure or hydraulic head generate power according to the expression

$$P = k\rho\phi gh$$

where ϕ is the flow rate of water, h is the hydraulic head, g is the acceleration due to gravity, ρ is the density of water, and k is a coefficient of efficiency determined by the type of turbine, facility design, and the dynamic flow and head conditions at which the turbine is operated.

Power extracted by waterwheels and other hydrokinetic devices having negligible head depends primarily on the flow rate of the water passing over, under, or through them. Thus the power generated is proportional to the water's kinetic energy, which can be calculated using the expression

$$P = ½\rho A v^3$$

where P is the power, ρ is the density of water, A is the cross-sectional area of the flow, and v is the water velocity.

Medium- to high-head projects, especially in relatively low-flow regimes, often employ *impulse* turbines, in which the water is directed through the air at high velocities onto the turbine blades by jets that leverage the substantial water pressure (contributed by the head). Low- to medium-head projects and those with the highest flows (which require less head to generate acceptable power as a result) commonly use *reaction* turbines, in which the turbine blades are fully immersed in water and enclosed in a pressured casing. The pressure differences across the blades create lift forces that drive the rotation of the runner. Widely used turbine types operating in these flow and head regimes are the Kaplan (for heads between 2 and 40 m; dating to 1913) and Francis (for heads between 10 to 350 m; dating to 1849) reaction turbines and the Pelton (50–1300 m) impulse turbine, although a number of alternative or derivative designs exist. Figure 2(http://en.wikipedia.org/wiki/File:Water_Turbine_Chart.png) illustrates the approximate ranges for head and flow ranges for which particular turbine types are appropriate.

5.12.2.2 Hydropower across Scales

That both axes of Figure 2 are logarithmic indicates the remarkable variation across scales and conditions for which hydropower devices can be applied. The largest hydropower plants generate more energy than any other type of power-producing facility (Three Gorges Dam at 22.5 GW, Itaipu Dam at 14 GW, and Guri Dam at 10.2 GW), whereas the smallest may power only a portion of the energy needs of a single home. The uses, benefits, impacts, and prospects of hydropower across these scales differ substantially.

5.12.2.2.1 Large Hydropower

The scale classifications of hydropower are approximate and vary regionally, but facilities from over 50 MW up to those exceeding 10 GW are generally described as large hydropower. These facilities require massive infrastructure, including large

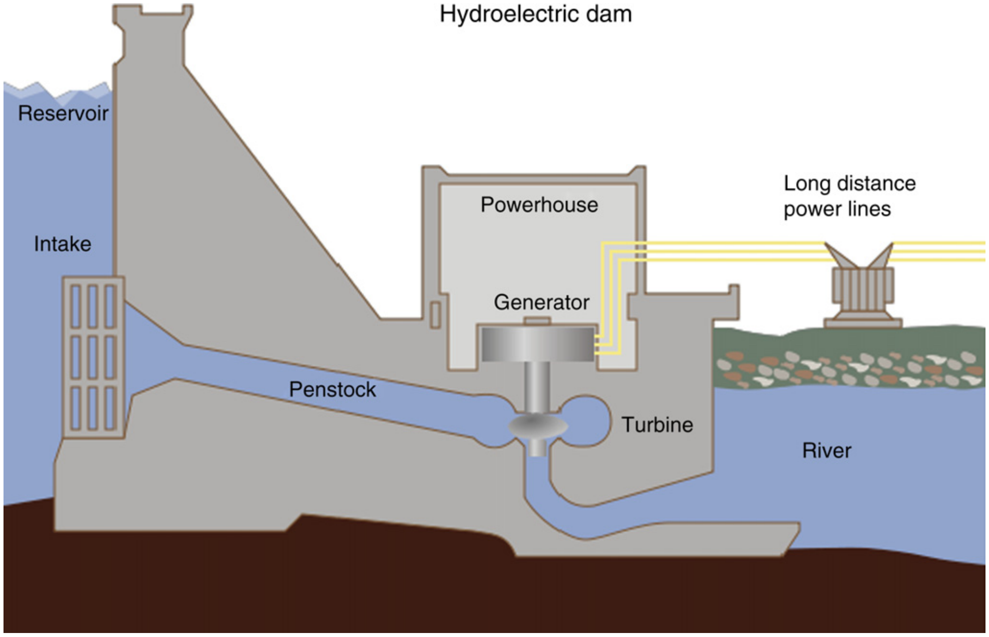

Figure 1 Schematic of a hydroelectric dam. Courtesy of http://en.wikipedia.org/wiki/File:Hydroelectric_dam.svg.

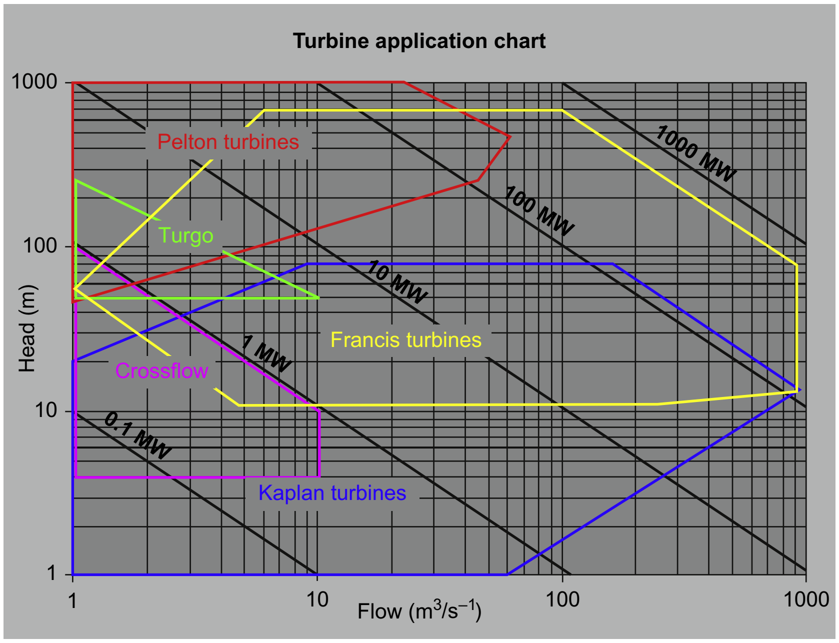

Figure 2 Head and flow range guidance for turbine application.

dams, large storage capacity, and large transmission lines, and their construction and operation typically cause large-scale multifaceted impacts in their watersheds and to the hydrologic cycle of the river that they regulate. Most are multipurpose facilities, and in some cases, hydropower generation is not the primary operational purpose. For example, the major projects in the PNW have traditionally been managed synergistically to support navigation, flood control, river and lake recreation, fisheries and other habitat protection, agricultural irrigation, municipal and industrial electricity demand, as well as hydropower. Such joint operations constrain both current power generation and the options available for power operations to adapt to future changes in energy demands or inflow variability. Owing to the cost of their construction and the multiplicity of stakeholders in such projects, most projects (although not all) in North America are owned by governments, typically in the form of federal agencies in the United States or provincial Crown corporations in Canada.

A useful hydropower system configuration often associated with large-scale plants, but also appearing in smaller, stand-alone forms is *pumped storage*, in which water can be moved between reservoirs at different elevations. At times of low electrical demand, excess generation capacity is used to pump water into the higher reservoir so that water can be released back into the lower reservoir (through a turbine) at times of higher demand. These systems are net consumers of energy, since they do not regain the energy lost in pumping water upward while generating. Yet pumped storage schemes provide a highly flexible, thus, important means of large-scale grid energy storage and serve to 'firm' the capacity of other energy generation systems to which they are linked. Energy that power systems can produce reliably is termed *capacity* and is far more valuable than energy that can be produced intermittently. Energy storage can smooth out the intermittency of resources that do not always generate, creating additional capacity, in a process called firming.

5.12.2.2.2 Small Hydropower

Hydropower is considered small if the capacity is less than 10 MW, although in regions such as the United States and Canada, the category includes capacities of up to 25 MW. Many small-scale hydropower plants are also multipurpose, although less frequently so than large-scale plants, and typically serve a community or localized industrial purpose. Many small hydro projects are run-of-river plants, in which a portion of the flow is diverted from a steep-gradient river and returned with high head through turbines farther downstream, while passing the remaining flow for environmental purposes. Environmental and social impacts generally scale with project size (e.g., storage, civil works, although this is not always the case: poorly designed projects can have impacts that are disproportionate to their scale, and this decreased environmental impact depends strongly on the balance between stream flow and power production. Thus small hydro projects have new expansion potential in some developed countries where new large-scale plants are infeasible.

Small-scale hydroelectricity production grew by almost 30% from 2005 to 2008, including 3 GW of new capacity in the United States (Renewables Global Status Report 2006 Update, REN21, published 2006). Although small projects, and particularly 'low-power' (<1 MW) projects, far outnumber and have greater new development potential than large hydro projects, they also make up far less of the aggregate capacity. **Figure 3**, which summarizes large, small, and 'low power' (<1 MW) projects in the United States, shows that it would take about a 50% increase in small hydropower to offset a 5% decrease in large-scale capacity. Small hydro developers may benefit in overcoming opposition to new projects by earning a certification of 'low impact' from various groups attempting to promote such a standard. The requirements may include impact criteria in the areas of river flows, water quality, fish passage and protection, watershed protection, threatened and endangered species protection, cultural resource protection, and recreation and existing infrastructure (see, e.g., http://www.lowimpacthydro.org/).

5.12.2.2.3 Micro, Pico, and Hydrokinetic Power

Smaller forms of hydropower exist, particularly for rural electrification purposes, in third world countries, or for reaching locations that are remote from any power grid or transmission. Categories include pico hydropower (<5 kW) and micro hydropower (<100 kW). These forms can provide power to an isolated home or a small community, or are sometimes connected to electric power networks. Many systems are run of river, with negligible pondage. Hydrokinetic technologies ranging from a few kilowatts to <500 kW represent a growth area in the United States. In late 2008, the City of Hastings, MN, installed the United States' first-ever commercial, federally licensed hydrokinetic power station, a 250-kW turbine located in the tailrace of a 4.4-MW US Army Corps of Engineers project. Only 2400 of the nation's approximately 80 000 dams have installed hydropower capacity, and many also provide streamflows through irrigation ditches and other infrastructure. Because the civil works for many of these sites exist and the hydrokinetic devices more easily meet low-impact standards, the US hydropower industry envisions a spread of devices, although the overall impacts on US capacity may be small. Offshore hydrokinetic energy in the form of wave or tidal power also holds potential for future hydropower growth. Wave technologies are newer and more experimental than tidal technologies, which now support local energy supplies in countries such as Canada and Scotland.

5.12.2.3 The Historic Growth of Hydropower

Hydropower advocates cite numerous benefits relative to other forms of electricity generation. Over 2000 hydroelectric power plants in the United States currently supply approximately half of the nation's renewable electricity (http://en.wikipedia.org/wiki/Hydroelectricity–cite_note-REN21-2011-0). Like other renewable energies, hydropower generation avoids carbon dioxide emissions that are a by-product of thermal generation: the 250 TWh of hydroelectricity generated in the United States per year, for instance, would emit 243 million metric tons of carbon dioxide, or about 3.5% of the US total emissions. This estimate assumes approximately 7 billion metric tons per year (http://en.wikipedia.org/wiki/List_of_countries_by_carbon_dioxide_emissions), 10 296 Btu/kWh for fossil-fueled steam-electric plants, 207.7 lb of CO_2 per million Btu (EIA, Annual Energy Review, 1995), and 250.6 TWh of hydroelectric generation per year (http://en.wikipedia.org/wiki/Hydroelectricity), if produced by a coal-fired steam plant. Unlike other fuels, hydropower that is integrated into a multipurpose reservoir project can also subsidize secure water supply, irrigation for food production and flood control, and societal benefits such as increased recreational opportunities and improved navigation. Hydropower is one of the cheapest and most efficient energy sources, and the fuel (streamflow) is not subject to market price variation. One of the most important benefits of hydropower is that, as a form of energy that can be ramped up or down quickly and also stored, it almost uniquely provides important additional services to electricity networks (discussed further in Section 5.12.5).

Nonetheless, in retrospect, the twentieth century bracketed the major period of hydropower development, with early generators having been installed near the turn of the century and steady growth in new capacity occurring until the 1970s (**Figure 4**). For example, in 1920, 40% of the US electrical supply came from hydropower. Hydroelectric generation is by

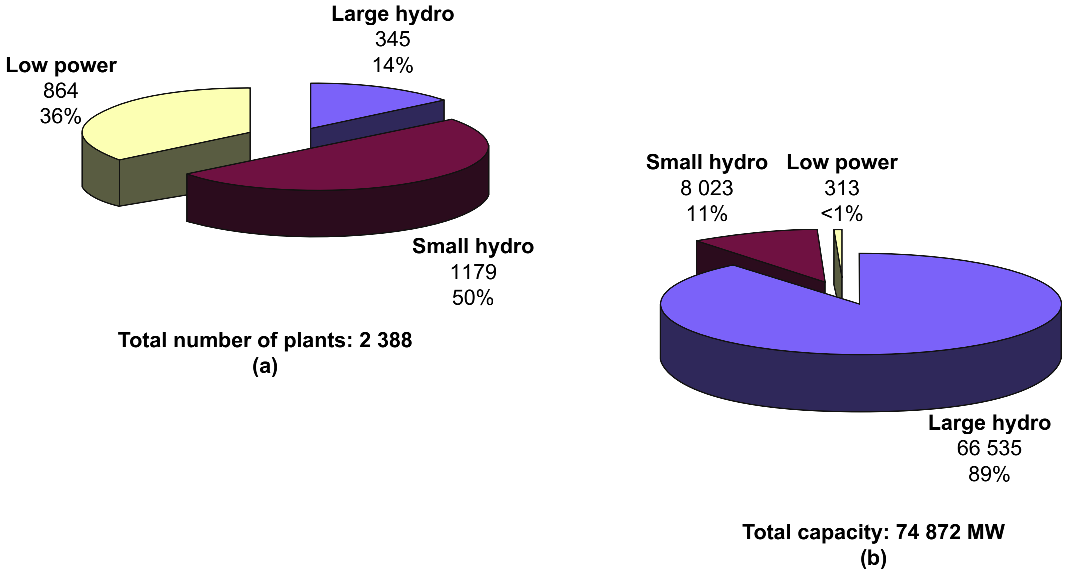

Figure 3 Distribution of US hydroelectric plants by power class in terms of (a) number and (b) total power class capacity (Hall, D.G., and K.S. Reeves, 2006: *A Study of United States Hydroelectric Plant Ownership*, Idaho National Laboratory, US Department of Energy, Idaho Falls, INL/EXT-06-11519).

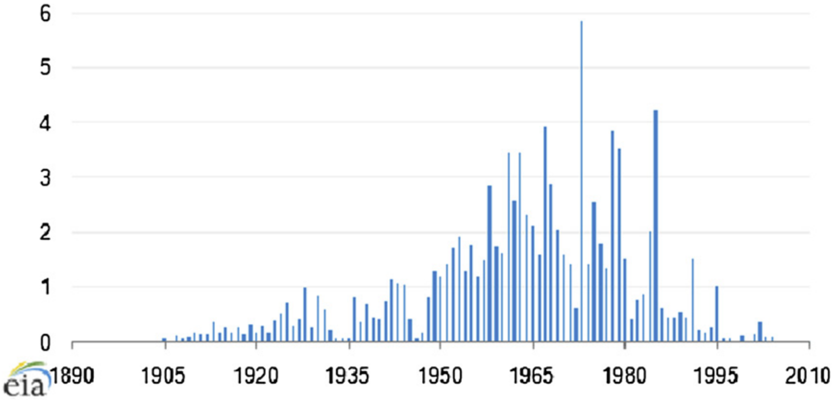

Figure 4 Current (2010) capacity (in gigawatts) of large-scale hydropower generators in the United States, by initial year of operation (http://www.eia.gov/energy_in_brief/hydropower.cfm).

now one of the oldest energy resources in the United States, however, and hydropower facilities represent approximately 70% of generating plants over 60 years old (US Energy Information Association). After dropping abruptly in the 1970s because of increasing regulations and resistance from environmental groups, most hydropower development eventually slowed to a halt by the 1990s. Hydropower capacity in the United States has not risen appreciably since.

Given the dependence on both potential energy and streamflow, hydropower is concentrated in wetter regions and regions with steep terrain. As illustrated in Figure 5, these mainly include the western and eastern mountain ranges of North America, with relatively limited production in the continental interior. The highest regional capacity occurs in the PNW (the focus of this chapter), which includes the southern portion of the Canadian province of British Columbia (BC), and Washington, Oregon, and Idaho of the United States. The steep, wet environment of the PNW enables hydropower to supply nearly all of the region's energy needs, particularly in a wet year.

Although hydropower capacity grew for most of the twentieth century, energy demand of all forms, including hydroelectricity, far outpaced this growth. Since the 1950s, electricity demand was met by thermal fuels, primarily coal-fired generation and natural gas. Natural gas capacity in particular has seen large increases in the last two decades (Figure 6), in part because it is cheaper and is considered cleaner from an emissions standpoint than coal-based generation. This trend is likely to continue owing to recent advances in hydraulic fracturing as a means to extract gas from deep-lying shale formations. Shale gas extraction is projected to grow fourfold over the next 25 years, based on an estimate of 827 trillion cubic feet of technically recoverable reserves (Annual Energy Outlook 2011, EIA). Environmental resistance to shale gas extraction methods is currently rising, however, as impacts such as groundwater contamination are beginning to be understood and

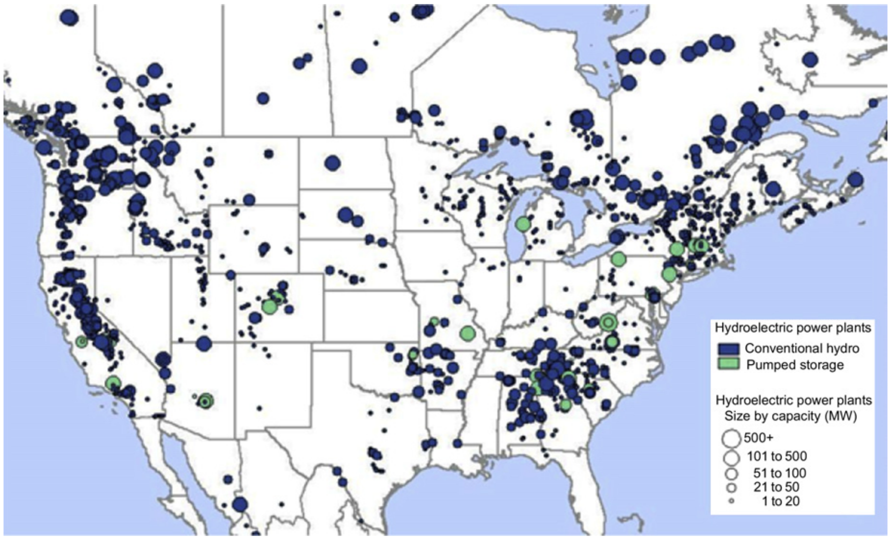

Figure 5 Hydroelectric generators in and around the United States. (U.S. Energy Information Administration, Today in Energy, June 10, 2011).

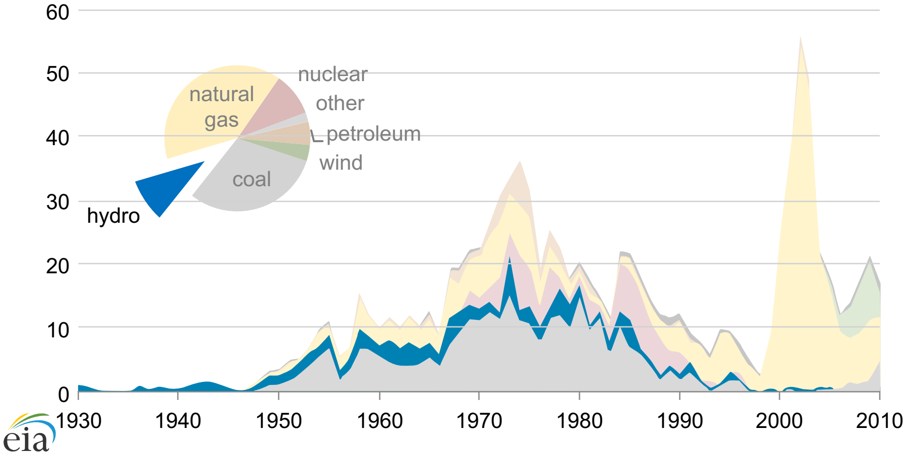

Figure 6 Current (2010) capacity by initial year of operation and fuel type (in gigawatts). Source: U.S. Energy Information Administration, Form EIA-860 Annual Electric Generator Report, and Form EIA-860M (March 2011 Electric Power Monthly).

the emissions associated with shale gas extraction and use are better quantified (current estimates range from half to double that of coal generation).

Although the diminishing marginal value of new hydropower sites was another factor in the decline of hydropower development, viable locations for new hydropower facilities do exist. The United States, for example, has an estimated potential to add 30 GW, about 40%, to current conventional hydropower capacity (US Department of Energy's Hydropower Program assessment report, as reported in US Bureau of Reclamation, 2005). The existence of significant potential for future hydropower development implies that the future of hydropower depends in no small measure on the constraining forces that have brought the virtual moratorium on new large-scale plants in the developed world. These forces are discussed in the following section.

5.12.3 Environmental and Social Consequences of Hydropower

Despite an appreciation of hydropower's benefits, the rapid growth of hydropower in the twentieth century spurred rising opposition from environmental groups. This section describes several of the key elements fueling negative societal perceptions of hydropower.

5.12.3.1 Environmental Impacts of Dams

There is little argument over the nature of many of the physical changes wrought by the construction and operation of a reservoir, as these can be quantified by measurement or modeling, or entail recognizable alterations of the watershed or landscape. Whether these represent adverse impacts, however, may be a matter for debate, reflecting the social and political values of those affected by the reservoir, and in some case of interest groups around the globe. In a modern example, concerns voiced during the construction the Three Gorges Dam in China illustrate modern antidam environmental, social, and political sentiments. That the 20 GW of hydropower capacity may replace 'dirtier' electricity sources (e.g., coal burning) or enhance rural electrification is generally viewed as beneficial, but detrimental environmental consequences include the flooding of riverine habitats; fragmentation of natural surface water systems, habitat, and fisheries; and alteration of the natural hydrologic cycle and sediment budgets. These and other types of impacts, some of which are more general, are described below.

5.12.3.1.1 Conversion of a Free-Flowing River to a Reservoir

Perhaps the most obvious consequence of hydropower development that requires damming a river is the creation of a static body of water (i.e., an artificial lake or reservoir) that inundates previously riparian and upland areas and submerges a reach of a previously flowing river. While the scale of this change to the existing natural system varies with the scale of the impoundment, the disturbance significantly alters associated aquatic habitat and adjacent terrestrial ecosystems. Depending on the size of the reservoir storage, the watershed's natural cycle of runoff (driven by temporal climatic variation and watershed characteristics) is typically disrupted. Because the reservoir water surface is larger and detained water is exposed for longer to evaporative forces than the original river surface, the outflow of the river may decrease significantly, particularly in arid areas. Evaporation from Colorado River's Lake Mead, for example, depletes the average flow volume by an estimated 8% each year (Westenburg, et al., 2006). To date, over 400 000 km^2 of the Earth has been flooded by dams.

5.12.3.1.2 Fragmentation of River Ecosystems and Impact on Fisheries

Added to the alteration of the timing of the hydrologic cycle, which can impact dependent species, large and small dams create a barrier obstructing the upstream and downstream movement of migratory river animals and anadromous fish such as salmon. Dams block fish migration upstream to spawning areas, and the relatively slack water in reservoir pools exposes fish to predation and unnatural temperature and water quality regimes, with consequent impacts on reproduction and the species population. In the Columbia River system, approximately 55% of the watershed area is no longer accessible to ocean-going salmon as a result of dams. Salmon species have vanished from many PNW streams, and other stocks have declined since the advent of the dams. Dam-related efforts to combat salmon stock loss typically include the installation of artificial 'fish ladders' and specific release operations thought to enhance fish viability (such as flushing releases during outmigration), and more extreme measures include barging or trucking of salmon to circumvent the dam. Substantial federal funding since the 1970s also supported the development of 'fish friendly' turbines that marginally increase the survival of fish passing through the powerhouse. Estimates of salmon recovery costs in the PNW range from \$6 billion to over \$10 billion during the past 30 years. While fish ladders and other measures are clearly beneficial, the overall effectiveness of salmon recovery measures remain unclear, in part because other factors such as ocean and downstream harvest of salmon and sea surface temperatures (SSTs) also affect salmon populations. Fish species such as lake trout may thrive in the reservoir environment, however, supporting recreation but representing a species shift from pre-dam conditions.

5.12.3.1.3 Alteration of Sediment Budgets and Water Quality

Rivers transport sediment down their riverbeds, allowing for the formation of riverbanks, river deltas, alluvial fans, braided rivers, oxbow lakes, levees, and coastal shores. Dams obstruct the flow of sediment downstream, leading to downstream erosion of these sediments while increasing sediment build-up in the reservoir. While the rate of sedimentation varies for each dam and each river, all reservoirs that were not designed with a flushing capability develop a reduced water-storage capacity, hence a decreased ability to produce hydroelectric power or to store water for irrigation, water supply, and flood control. The reduction in sediment supply downstream also alters shoreline and river delta ecosystems and can cause coastal erosion.

Reservoir water may be warmer in the winter and cooler in the summer than it would be otherwise, which affects the plant and animal life present in both the reservoir and, via releases, those in the river downstream, leading to losses among endemic species. In the PNW as in many regions, maintaining river temperatures and other water quality parameters (such as dissolved oxygen) within limits deemed acceptable by biologists and ecologists represents a common constraint to reservoir operations.

5.12.3.1.4 Greenhouse Gas Emissions

Although widely regarded as clean energy relative to thermal fuels, reservoirs do contribute to greenhouse gas (GHG) emissions as a result of releasing methane from anoxic sedimentary layers at the bottom. Although research in this area is still relatively sparse, some estimates suggest that for warm-climate reservoirs with large surface areas and substantial sediments, these releases can be greater than those from oil-fired generation of equivalent capacity.

5.12.3.2 Social Consequences of Hydropower Development

Hydropower brings both societal benefits and challenges. Abundant renewable energy is an obvious advantage, and stakeholders in multipurpose reservoir systems additionally depend on water supply and flood control functions. However, social losses also exist, and extend beyond the environmental concerns discussed in the previous section. Most energy-related facilities (including clean energies such as wind farms) are rarely popular in close proximity to human habitation, but many, such as gas-fired generators, have a much smaller footprint than a large hydropower facility. The largest hydropower schemes, in contrast, may require the displacement of large numbers of people and the demolition of their towns or villages. China's Three Gorges project involved the dislocation of over 1 million people, a record for dam-related construction.

In addition to long-term resettlement, the construction phase of hydropower is notorious for impacts on nearby population. Although construction may provide employment for a number of years while the project is built, and a small number of positions associated with dam operation afterward, hydropower development, as an industry saying goes, "is synonymous with delay." Hydropower development requires a complex orchestration of financing, permitting, and political support, in addition to multiple kinds of engineering effort (civil, electrical, and geotechnical) that in some cases proceed in the face of significant uncertainty. Large hydropower facilities commonly take longer than a decade to build, during which the lives of nearby inhabitants are affected.

After a project is built, nearby human populations may also be affected by increases in disease vectors such as mosquitoes carrying malaria (especially in tropical areas) that breed in the slack water created by the reservoir pool. Other deleterious ecological effects that cascade into human impacts include changes in the water inputs to lands downstream of the reservoir. Savannahs and agricultural lands that depend on periodic flooding from a seasonal runoff cycle may be altered, degrading grazing lands and fields historically cropped during flood recession, depriving farmers of their livelihood and leading ultimately to further resettlement.

The hydropower industry is cognizant of the need for social approval for new development and the potential for organized opposition to delay or block a project, with financial consequences for all parties involved. Steps to win and demonstrate local to regional support for projects are now a prominent feature of hydropower development for both small- and large-scale projects.

5.12.4 The Regulatory Environment

Environmental and social concerns about hydropower development impact hydropower growth via their incorporation into governmental regulations. The evolution of the regulatory environment, spurred in part by issues described in Section 5.12.3, has shaped the outlook for hydropower today. Regulations reflect a broader body of policy objectives relating to water resources, many of which predate the modern hydropower industry. The use of water resources in the PNW (as elsewhere) is regulated to account for environmental, economic, and social needs; to strike a balance for competing the use of water among multiple stakeholders of large reservoir systems; and to accommodate technological advances.

While federal policy regarding interstate water management in the United States dates to the constitutional landmark decision under the Commerce Clause in 1824, its implementation was initially limited to the development of navigation and its safety. By the middle of the nineteenth century, the federal responsibility included flood control (via the US Army Corps of Engineers, USACE). Early in the twentieth century, the advent of the hydroelectric industry and the need for irrigation in the western states introduced new and often competing demands for water resources, and conservation began to be an objective for policy makers.

Today, the regulations and interests of various agencies and organizations govern the hydroelectric industry. Social and environmental needs are evaluated by a number of federal and state agencies, First Nations, and state water quality and other agencies. In the United States, these include, but are not limited to, the Environmental Protection Agency (EPA), the Department of Agriculture's Forest Service, the Department of Commerce's National Marine Fisheries Service, and the Department of the Interior. Among these groups, the Federal Energy Regulatory Commission (FERC) is the major energy regulatory body in the United States, with responsibility for licensing or relicensing the project construction and operations oversight of existing projects, including dam safety inspections and environmental monitoring. FERC authority derives from the Federal Power Act (FPA) of 1920. FERC licenses have terms ranging between 30 and 50 years, a relatively long period but often shorter than a project's design life. The Electric Consumers Protection Act (ECPA) of 1986 expanded focus beyond power objectives to include mitigating environmental and social impacts in the hydroelectric licensing process, as well as enhancing energy conservation, fish and wildlife, recreational opportunities, and the preservation of other aspects of environmental quality. Despite several reforms (e.g., in 2003, FERC approved the current 'default' licensing process – the *integrated licensing process*) to streamline the licensing process, the time required to obtain a hydroelectric license has grown from 2 to 4 years, and the licensing cost has doubled, making hydroelectric facilities less competitive with other conventional power-generating technologies. By comparison, natural gas generation is faster to permit and build, and consequently carries less developmental risk and potentially lower costs.

In British Columbia (BC), Canada, government legislation restricts the development of large hydro facilities at particular sites, although most existing BC Hydro projects have water/use licenses that have been issued for perpetuity. Like any other type of generation, hydropower needs to comply with the environmental regulations, including the BC Environmental Assessment Act (for plants with installed capacity greater than 50 MW) and the Canadian Fisheries Act (for hydro developments impacting fish). The BC policy framework derives from the BC Power Authority (BC Hydro) and long-term acquisition, and integrated resources plans are regulated by the BC Utilities Commission. In general, the government energy policy goal is to reduce GHG emissions; increase the demand side management; encourage utilities to produce, generate, and acquire electricity from clean or renewable sources; encourage utilities to develop adequate energy transmission infrastructure and capacity; and encourage utilities to use innovative energy technologies that facilitate electricity self-sufficiency and meet environmental requirements. Consequently, hydro generation, both large scale and run of river, is a part of the integrated resource plan in BC.

Although the regulatory environment is more permissive in BC than in the United States, the hydroelectric industry has shifted from development of large dams to improving operation and increasing the efficiency of existing assets and small upgrades at existing plants. In addition, some development of small dams with run-of-river power plants has occurred, albeit without significantly increased total hydro generation capacity. Where new project development in North America does occur, it illustrates the modern realities of regulatory compliance. Near the PNW, one example is the proposed 1100-MW Site C power station in northern BC, Canada, to be built by BC Hydro with planned completion in 2021. The project will undergo an independent environmental assessment (EA) process that includes multiple opportunities for consultation and input by the general public, Aboriginal groups, communities, property owners, and stakeholders. Like any proponent of a large project with potentially significant impacts, BC Hydro will identify and assess possible project effects – environmental, economic, social, heritage, and health – and opportunities to provide lasting benefits for the region and Aboriginal groups. Where deleterious effects cannot be avoided, BC Hydro must identify and propose options for mitigation. Even given sufficient hydrologic resources to support an economically productive project, failure to convince stakeholders may result, at a minimum, in project delays and cost increases, and ultimately, the outcome of the EA process could be either approval or rejection of the proposed project.

5.12.5 Hydropower in the Context of Renewable Energy

Hydropower, wind, solar, biomass, geothermal, and other forms of renewable energy have existed for decades, but growth in non-hydropower renewable energy has rapidly accelerated in recent years. The sector's growth is motivated by social, political, and economic interests such as energy security and by concern over anthropogenic climatic change, and is supported by advances in renewable technologies. Hydropower still accounts for over half the modern renewable energy resources (Figure 7), which supply roughly 20% of the world's electricity (see Section 5.12.2 Harnessing Hydropower: An Overview), but hydropower in developed nations has not shared in the recent boom.

In the United States and other nations, renewable energy growth has been promoted via deliberate policymaking to spur a switch from thermal energy sources. Many US states have incentivized renewable energy development using Renewable Portfolio Standards (RPS) regulations, which require utilities to generate a certain fraction of energy from renewable energy sources, such as wind, solar, biomass, geothermal, and, to a degree, small hydro. No RPS exist yet at the federal level, and state-level RPS vary from nonexistent to aggressive (e.g., California's 33% by 2030). Renewable power is also incentivized by Production Tax Credits (PTC) that are proportional to the power generated and by other legislated measures. For solar power, incentives come in the form of feed in tariffs, which compensate generation that is supplied to the regional grid. In contrast to the other technologies, however, hydropower has been excluded or de-emphasized in many US renewable incentives. The rationale is not hard to fathom. In Washington State, for example, the RPS objective is for 15% of energy use to come from renewable sources by 2020 (http://apps1.eere.energy.gov/states/maps/renewable_portfolio_states.cfm) – yet hydropower already represents 75% of the current electricity resource; thus including existing hydropower would obviate the RPS initiative. The hydropower industry has fought for recognition of some aspects of hydropower as renewable, winning some concessions (e.g., for plants within the small hydropower category, for turbine capacity upgrades to larger plants, and for small-scale hydrokinetic technologies), but without achieving parity with other renewables. Regulatory and market incentives for small, run-of-river hydro exist with certain constraints, but are not in place for the development of new large-scale hydropower generation.

The renewable supply side resources that can provide utility-scale energy (e.g., sufficient to power at least a small town) at a reasonable cost are wind, hydro, ocean (tidal and wave), solar, geothermal, and biomass. Since the only incentivized forms of hydropower are primarily small hydro facilities or hydrokinetics, the remaining clean energy options are biomass and geothermal resources, which have their own drawbacks (scale, fuel availability), and wind and solar power, which are intermittent – that is, subject to large variations on timescales of minutes to days.

Power systems are extremely complex. The mechanisms responsible for their control and transmission enforce system stability by continuously adjusting the supply of electric energy to match the instantaneous, aggregate fluctuating electric demand of customers (i.e., the load). Stable operation of the system thus requires the ability to raise or lower the output of generating units to respond to fast fluctuations in load, as well as a 'spinning reserve' of power that can be brought on line (dispatched) relatively quickly to meet the load in case of unplanned loss of significant generating unit or a major transmission line. The activities and functions necessary for maintaining system performance and reliability are called *ancillary services*.

Intermittent resources do not have energy storage. Generation is driven by physical phenomena – essentially, the weather – thus the prediction and commitment of intermittent renewable power for any future period (even an hour ahead) carries uncertainty, with forecast accuracy typically diminishing with forecast lead time. Despite small, non-utility scale advances in battery technology, intermittency particularly characterizes wind and most solar power, and less so small run-of-river hydropower. The combination of renewable power variability, lack of storage, and relatively high uncertainty of generation forecast makes it challenging to integrate wind (and other intermittent renewable) generation into established practices for long-term energy planning, in addition to system operations.

While the intermittent resources do provide, in the time-averaged sense, reliable energy supply, their ability to provide capacity – *dependable capacity at high reliability* – is limited unless reserves are also available. Yet systems need both energy and capacity: in long-term planning of electric power systems, overall reliability is often measured in terms of the probability that the planned generation capacity will meet the future peak load. The installed capacity of intermittent resources may exceed a projected load, but there is no guarantee that the capacity will be available at the time of the demand. For example, wind farms in the PNW generate more energy at night than during the peak energy demand hours during the day.

At large conventional hydropower plants and smaller pumped storage facilities, the existence of a reservoir (energy storage) or reverse pumping capacity provides much needed flexibility to buffer variability in intermittent generation. Storing water (energy) when it is not needed and generating when energy is needed is economically attractive (the price of electricity drops when the demand is low and rises at the times of high demand). Hydropower plants also have a very fast response time (they can turn on and off generation quickly),

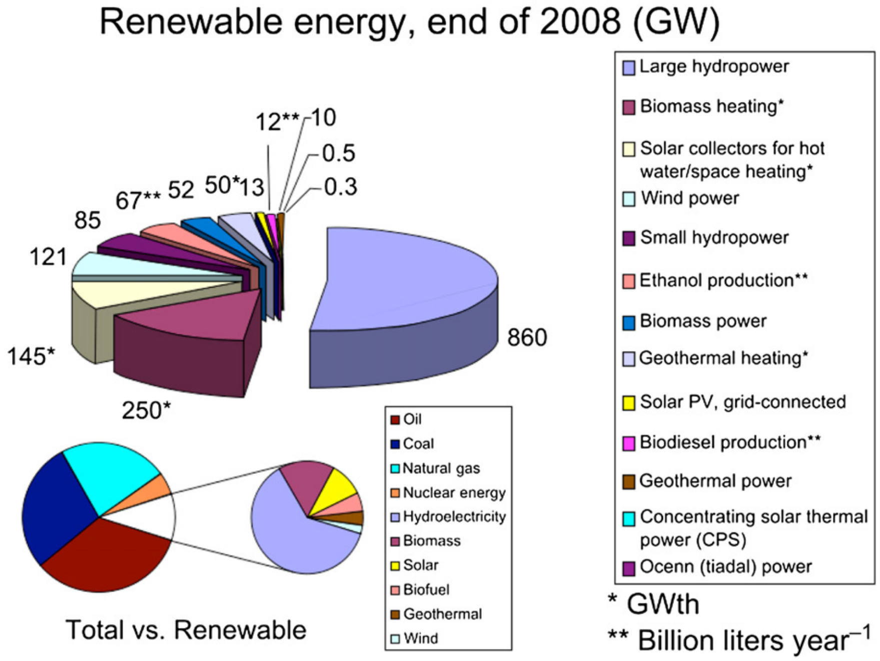

Figure 7 Global renewable energy (in GW) in 2008. Source: http://en.wikipedia.org/wiki/File:Ren2008.svg.

which makes them a prime choice for energy reserves. Gas-fired power plants, another suitable choice for energy reserves, can be subject to supply disruptions or price fluctuations. Their response time is not as quick as that of hydropower plants and they are a less attractive solution from the standpoint of GHG emissions. Nonetheless, an unappreciated consequence of rapid wind farm growth in areas without sufficient hydropower is a requisite expansion of gas-fired generation. In Europe, the penetration of wind and solar power into energy markets has depended on access to hydropower (e.g., in countries such as Norway or in pumped storage facilities) as a means of grid integration. Even in areas with currently sufficient hydropower, the existing hydro systems have a physical limit on providing reserves for the integration intermittent resources. In the Pacific Northwest, for instance, the hydropower system is nearing an integration limit, given current multiobjective operation constraints, as 6000 MW of wind energy comes on line. New flexible resources to compensate for intermittent energy supply will be needed in the future.

Large hydropower reservoirs provide the most flexible and potentially economical energy storage today, and this role is relatively new in an industry that does not change quickly. Owing to regulatory constraints (see Section 5.12.4), large hydropower is currently a more expensive option for renewables integration than gas-fired plants. Run-of-river reservoirs can also serve as storage, but their contribution is more limited and costlier than that of large hydropower. Pumped storage hydro can provide integration services and can be economical if the spread between the peak-hour electricity prices and nonpeak-hour electricity prices is high. The licensing and construction of new pumped storage facilities remains very difficult, however, and only 34 plants exist in the United States.

It is clear that hydropower could play a critical role in a transition toward the renewable energy future that is envisioned in current market incentives and renewable energy policy. The water and power management agencies, regulators, and the hydropower industry are now grappling with the complexities of defining that role, given social and environmental constraints established decades ago, as the footprint of intermittent renewables continue to grow.

5.12.6 Hydropower in the Face of Nonstationarity

Changing societal values and awareness of environmental impacts have significantly shaped the evolution of hydropower, yet hydrologic and climate research increasingly raises other concerns that may alter the outlook for hydropower. Since the later decades of the twentieth century, global change research has brought increasing attention to the concept of nonstationarity in hydroclimatological and land surface elements of the Earth system. This chapter adopts the concept of nonstationarity from an engineering context: that the practice of using statistical descriptions of system behavior based on the relatively short record lengths (often 30–50 years) for long-term planning is invalid if system properties vary on longer timescales than were measured by the observed record. This focus on non-stationarity has been highlighted in part by international groups such as the Intergovernmental Panel on Climate Change (IPCC), which placed a primary emphasis on changes in climate while also describing causative, consequential, or interrelated changes in other physical variables. Like other sectors having operational dynamics that are influenced directly or indirectly by changes in geophysical processes, hydropower is sensitive to nonstationarity. This section provides perspective on the major sources of geophysical nonstationarity that affect hydropower: low-frequency hydroclimatic variability, climatic change, and large-scale land surface change or disturbance.

5.12.6.1 Terrestrial Hydrologic Variability: Land-Use and Landscape Change

Processes occurring at the land surface, in some cases partially related to climatic variability and in other cases not at all, can also induce strong long-term changes in river discharge and dynamics. Land-use and land-cover (LULC) change is a particularly clear example. It has long been known, for instance, that urbanization – the replacement of permeable land covers (forests, wetlands, agricultural crops, etc.) with impermeable surfaces (rooftops, paved road surfaces, etc.) – generally leads to a particular set of related hydrologic responses, including flashier streamflows, higher peak flows with increased erosion and flooding potential, and lower baseflows with potential implications to aquatic habitat availability.

In the PNW, forestry practices represent another source of large-scale systemic change. In general, forest harvest in a catchment has been shown to yield greater overall water supply, faster snowmelt, and higher peak flows. These hydrologic changes result from the removal of vegetation (which reduces sublimation and evapotranspiration), soil compaction (which reduces infiltration), increased insolation due to canopy loss, and road building (which channelizes runoff, speeding overland flow), among other physical changes. There are exceptions to these effects, and they damp out after a number of years as understory and then overstory recover. Recovery times (in terms of hydrology) to such disturbances can range from a decade to generations, depending on local circumstances. A detailed review of these impacts is provided by Moore and Wondzell (2005).

Another important LULC process is large-scale deforestation and associated hydrologic impacts of species of insects such as the mountain pine beetle (MPB), which infest and cause mortality in trees. The MPB is a pest species native to northwestern North America that has devastated large tracts of forest in the last few decades. Current infestations are believed to be much larger than previous outbreaks, possibly reflecting a combination of past forest management practices and climatic changes. The increase in MPB infestations has also been linked to regional warming, and in particular the elevation of nighttime temperatures that, in colder decades, were low enough to kill beetle larvae. The hydrologic impacts are similar in nature to those often associated with forest harvesting (see above), but forest ecosystem changes associated with beetle kill are a multiyear phenomenon and involve more gradual and complex interplay of disturbances to the initial ecosystem. Current research on the near-term (1–10 year) hydrologic impacts in western North America is inconclusive; nonetheless, where the land cover may change from forest canopy to a sparse vegetation cover, harvest-related research suggests that greater watershed yields will result, together with earlier freshet timing in snowmelt areas. Beetle kill impacts may also be exacerbated by salvage logging operations. For a useful review, see Redding et al. (2008).

Glacier changes also have the potential to cause long-term hydrologic changes in the PNW. Overall, glaciers can be an important control on hydrograph form – increasing the water yield of a basin and providing increased flows in late summer when rain- or snowmelt-driven basins in the region are largely depleted of runoff generation sources. Today's mountain glaciers in the PNW represent the remnants of the last Pleistocene ice age. On this very long-term retreating trend are superimposed decadal- to centennial-scale increases and decreases in ice volume, and associated termini advance and retreat, generally associated with climatic fluctuations. Historically, the pattern in western North America has largely been a negative mass balance and glacial retreat under a warming climate. These changes have had significant effects on runoff in the PNW. However, while the glacier state is strongly connected to climate, internal glacier dynamics are also significant and complex, perhaps especially in larger ice masses such as the major ice fields that still cover portions of Canadian headwater basins to the Columbia River and parts of the BC Coast Range. One consequence is that even if historical warming trends were to cease today, glacier recession and the associated hydrologic changes would likely continue for decades. An extensive review of historical and potential future impacts of glacier change in western North America is provided by Moore et al. (2009).

Many, if not most, studies on urbanization, forest harvesting, MPB, and glacier change impacts on stream hydrology have focused on small basins. The manner in which these impacts integrate to larger spatial scales is less clear. Nevertheless, our current understanding of such processes leaves little doubt that they may impact certain types of hydroelectric generation, for example, new microhydro plants in glacier-fed watersheds in BC coastal mountain areas.

To the extent that some LULC processes are associated with climatic variability or change (such as MPB or glacier change), their effects may be regarded as pathways through which climate impacts hydrology, with an associated potential to alter hydropower prospects for better or for worse. The LULC changes may also affect local land–atmosphere feedbacks, such as alterations in the roughness driving turbulent fluxes in boundary layer meteorology, cascading into patterns of precipitation deposition, wind (hence evaporative demand), soil moisture, near-surface air temperature, and other phenomena that in turn further influence land surface hydrology and runoff. Such impacts may best be understood by incorporating these processes into comprehensive modeling approaches, although the complexity of the coupled earth system and sparsity of data for validation complicates the verification of model sensitivity results. In all, streamflow impacts resulting from LULC that determine; may influence the timing and quality of runoff more than the seasonal or annual inflow quantities on which hydropower capacity depends.

5.12.6.2 Hydroclimatic Variability and Trends

The atmosphere and ocean exhibit complex forms of variations over a wide range of time and space scales, ranging from second-to-second wind gusts at a particular headland to millennial- or even longer-scale oscillations or trends in global climate, with cascading effects at regional and local scales. Although more than a dozen modes or patterns of this variability have been proposed and/or identified, two in particular have been widely studied for their influence on climate and streamflow in the PNW: El Niño–Southern Oscillation (ENSO), which exhibits a cycle of a few years in length, and the Pacific Decadal Oscillation (PDO; Mantua et al. 1997), which, as the name implies, spans a few decades. Most hydropower infrastructure and operations are designed to manage variability on the interannual timescales associated with ENSO (i.e., buffering variation between dry and wet years). In contrast, 'low-frequency' decadal variability or longer persistence-related processes that appear as trends in conventional observational records present a challenge that is only implicitly addressed by storage and management. In addition, the vast body of research on climatic change suggests the possibility that observed long-term variations may now include a trend component resulting from anthropogenic GHG forcings of the climate system. The following subsections describe important features of these coherent modes of climatic variability, with emphasis on low-frequency modes and also summarize hydroclimatic findings related to climatic change. Note that interannual and 'low-frequency' variability are here separated because of their different impacts on water systems, but the definition of frequencies that are 'low' is context dependent. Interannual variability can also be considered 'low frequency.'

5.12.6.2.1 El Niño–Southern Oscillation

Although ENSO is a continuous process, three distinct ENSO states are customarily defined: El Niño (warm phase), neutral, and La Niña (cool phase). To first order, ENSO involves a 'sloshing' of warm surface water back and forth across the equatorial Pacific Ocean. During El Niño events, the easterly (i.e., west-directed) trade winds slacken or even reverse. Warm surface waters normally pooled in the eastern Pacific consequently flood westward into the central and eastern Pacific. Roughly the opposite happens during La Niña events, with strengthened trade winds and reinforcement of the usual upwelling of cool water in the eastern Pacific. Pacific SST anomalies during a recent La Niña are plotted in Figure 8.

The temporal signatures of ENSO are variable, but some consistent patterns exist. Individual El Niño and La Niña events typically last for 6–9 months but can in some cases remain in one phase for up to several years, and ENSO is generally described as being quasi-periodic and operating on timescales of about 2–6 years. Over most of the PNW, La Niña gives cooler winter and spring temperatures, on average. It also tends to yield higher winter precipitation, but this signal is less consistent, both year-to-year and between locations. El Niño effects are only roughly the opposite. Most importantly from a water resources perspective, any given ENSO event may exhibit local impacts that deviate – sometimes substantially – from the average for that type of event. Useful map summaries of typical ENSO impacts on Canadian and US surface temperature and precipitation are available through, respectively, Environment Canada (www.ec.gc.ca/adsc-cmda/default.asp?lang=En&n=45475BB4-1) and NOAA (www.cpc.ncep.noaa.gov/products/precip/CWlink/ENSO/composites/EC_LNT_index.shtml).

The overall effects on river flows in the region have been progressively refined in a substantial number of studies over the past 20 years (e.g., Redmond and Koch 1991; Woo and Thorne 2003; Fleming et al. 2007; Gobena et al. 2010) and are consistent with climate effects – i.e., toward higher flows in La Niña years and lower flows in El Niño years. The flow timing impacts of ENSO can vary from river to river, however. In predominantly snowmelt-fed rivers that are typical in many mountain and inland portions of the PNW, winter precipitation falls mainly as snow to be stored until the spring freshet, and the runoff impacts of La Niña show a commensurate delay. In predominantly rainfall-driven rivers, common in low-elevation coastal areas, the impacts are instead felt contemporaneously with the occurrence of the wintertime driving climate anomaly.

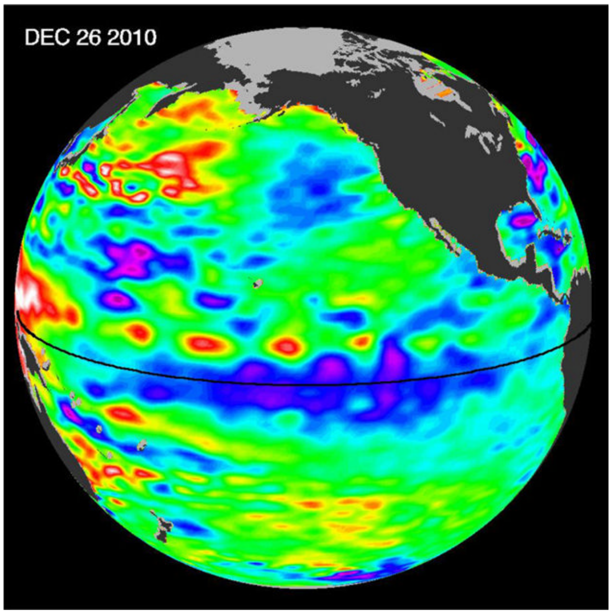

Figure 8 The 2010–11 La Niña event appears as a band of cool water (marked in blue hues) along the equator in this view of the Pacific Ocean from space. Courtesy of NASA/JPL-Caltech.

In medium- to high-elevation rivers, where snowmelt contributes substantially to flow, the temperature impact of La Niña can additionally be important. Many PNW rivers have both a winter rain freshet and a spring snowmelt freshet. Cooler temperatures can cause a greater proportion of the winter precipitation to fall as snow rather than rain, potentially shifting runoff from winter to spring. For such mixed-regime rivers, as well as inland and high-elevation basins dominated by snowmelt, cool winter–spring temperatures also shift the freshet timing – with cold-phase years, for example, typically showing delayed freshets. Again, the effects of El Niño are generally but not exactly opposite. Because ENSO imparts a clearer and more consistent signal to temperature than to precipitation, the corresponding river flow effects (i.e., on flow timing) are in general more reliable.

ENSO is the leading mode of interannual-frequency planetary climatic variability (Wallace and Thompson 2002; Hoerling et al. 1997). Owing to the predictability of ENSO effects on climate and flow, operational ENSO-based forecasting is conducted at a number of institutions using a variety of deterministic and statistical models. Summaries of current conditions and forecast compilations and interpretations are presented, for example, by NOAA's Climate Prediction Center (www.cpc.ncep.noaa.gov/products/analysis_monitoring/enso_advisory/) and Columbia University's IRI (iri.columbia.edu/climate/ENSO/

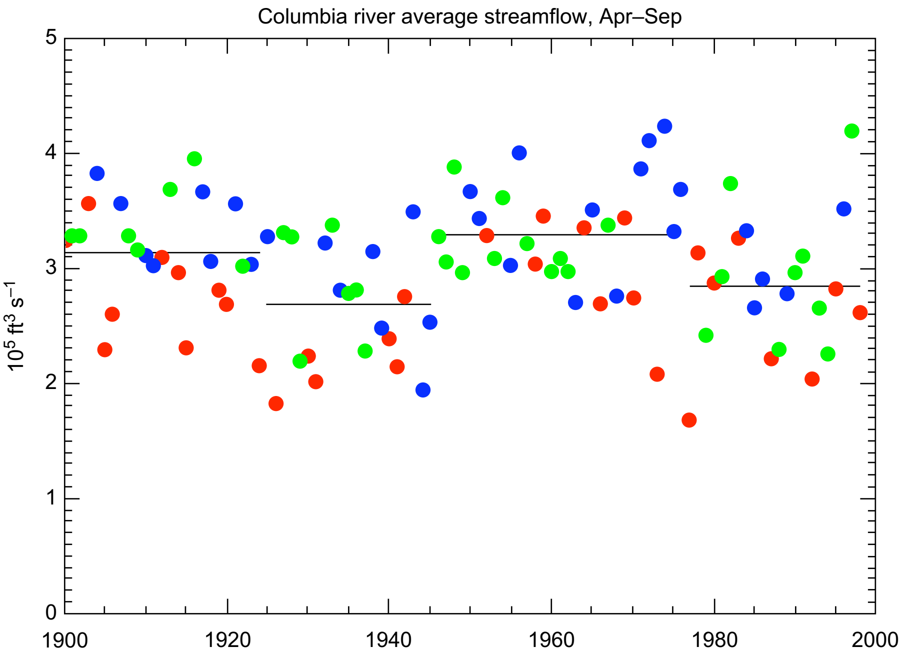

Figure 9 The influence of ENSO and PDO on Columbia River naturalized summer streamflow at The Dalles, Oregon. The horizontal lines show average streamflow over PDO epochs (cool: 1900–25, warm: 1925–45, cool: 1945–77, warm: 1977–95). Point color indicates year type: El Niño (red), La Niña (blue), and neutral (green). Courtesy of University of Washington Climate Impacts Group (http://cses.washington.edu/cig/pnwc/pnwwater.shtml).

currentinfo/SST_table.html). ENSO-attributed climatic variations can produce large variations in PNW hydropower; thus, forecasting is an important input for management in a wide range of climate and water-related sectors and represents an active source of advances in hydropower management efficiency.

5.12.6.2.2 Pacific Decadal Oscillation

The second major form of coherent climatic variability affecting the water resources and hydropower of the PNW is the PDO. The PDO is manifested as an east–west dipole in North Pacific SST. Whitfield et al. (2010) provides a recent and thorough review of the PDO and its impacts on water resources in western Canada; some of the major salient points are briefly discussed below.

Like ENSO, the PDO arises from oscillatory dynamics within the Pacific Basin, involves an east–west movement of Pacific surface water temperature anomalies, and has similar signatures in the surface meteorology and hydrology of the PNW. Figure 9 shows that warm ENSOs and PDOs tend to decrease streamflow and cold events tend to increase streamflow, and also illustrates their different temporal variability. ENSO consists of cold- and warm-phase episodes of at most a couple of years in duration that are generally punctuated by neutral years, whereas the PDO has been characterized as abruptly shifting between warm and cold regimes, each lasting for decades, typically without a neutral, intervening state. ENSO also differs in that it is defined by tropical Pacific variability, whereas the PDO is widely regarded as a North Pacific phenomenon. In contrast to perspectives on ENSO, the scientific community's knowledge about the fundamental origins of the PDO is limited. The PDO cannot be predicted with current methods, and current general circulation (e.g., climate) models (GCMs) struggle to reproduce the phenomenon. In fact, because the PDO remains defined solely on the basis of empirical data analysis and year-to-year climate is noisy, PDO regime shifts cannot be identified until they are several years in the past. Furthermore, researchers disagree over whether PDO regime shifts reflect true oscillatory behavior or are instead a misinterpretation of a stochastic red-noise process, mainly because the long characteristic timescale of the PDO – perhaps 30–50 years – means that most nonpaleo records are insufficient to distinguish between the fundamentally different models of PDO (Overland et al. 2006; Fleming 2009a).

Despite caveats and limitations, the PDO remains a highly valuable framework for understanding decadal-scale variability in the climate and water resources of the PNW. On average, warmer and drier conditions occur through much of the PNW during the PDO warm phase, giving earlier freshets, partial shifts of runoff timing from spring freshets to winter freshets in hybrid coastal hydrologic regimes, and lower overall water supply availability. The PDO cool phase is associated with loosely opposite conditions. Note that many of the complications identified above with respect to ENSO also apply to the PDO, including nonlinear teleconnections, sensitivity of hydrologic response to local hydrologic regime types, and the substantial within-epoch variability (i.e., not all years during a warm PDO regime will have warm PDO characteristics). Nonetheless, the PDO phase serves well as a general index of prevailing PNW climate and streamflow conditions.

5.12.6.2.3 Nonlinear Dynamics: Long-Memory Effects

On longer than decadal timescales, geophysical system memory is also relevant to outlooks for climate and hydrology.

The traditional notion of hydrologic 'memory' refers to the simple fact that river flows and other hydrologic variables change in a continuous fashion. For example, with a few exceptions, a relatively high flow right now is fairly likely to be followed by a relatively high flow a few hours or even days from now. Streamflow persistence effects arise from the regulation of hydrologic fluxes by watershed storages such as groundwater, snowpack, aquifers, and lakes, and may also incorporate persistence in driving weather or climate patterns. In statistical hydrology, the effect is often conceptualized as serial dependence and represented using linear low-order autoregressive models. However, such memory phenomena have also been observed on multidecade to near-century timescales in both hydrology and other disciplines within the physical, biological, and social sciences. The long-memory phenomena have been assessed using spectral analysis techniques and are variously termed long-term persistence (LTP), fractal dynamics, fractal noise, fractional Gaussian noise, fractional Brownian motion, $1/f$ (also $1/f^a$ or $1/f$-like) scaling, flicker noise, and the Hurst phenomenon, named for the findings of Harold Hurst regarding the temporal variability exhibited in the river stage records of the Nile River (Hurst 1951, 1957), which were over 600 years old. The physical processes driving such empirical effects are not well understood, but clearly stem at least in part from hydrologic 'resistances' or storages as well as similar effects in the climate system. Some seminal or otherwise useful examples of work in the field as relevant to hydrologic variability at a range of timescales include Hurst (1951, 1957), Mandelbrot and Wallis (1968, 1969a,b), Klemeš (1974), Booy and Morgan (1985), Livina et al. (2003), Cohn and Lins (2005), Koutsoyiannis (2006), and Khaliq et al. (2009).

The practical implication for hydropower of fractal dynamics in climate and watershed systems is similar to that of low-frequency (decadal or longer) variability. Both raise the specter of realizing extended periods of climate and streamflow that are not anticipated in facility design. That is, the observed streamflow and/or climate statistics on which water resources management system designs are typically based may fail to describe accurately the streamflow and climate regimes in which the projects will operate, causing capacity risk. If one is attempting to identify the available water supply to a proposed new hydro plant on the basis of a finite-length historical streamflow record spanning only one PDO regime, that record may contain a systematic high or low bias because the record is insufficient to identify low-frequency cycles with accuracy. Extreme events may be more frequent than inferred using standard statistical methods for flood frequency analysis. Long memory can lead to greater clustering of values (e.g., a more closely spaced sequence of flood years or longer droughts) than might otherwise be expected. It can also create apparent trends that complicate efforts to identify anthropogenic global climate change (AGCC) effects in long-term historical data records, even using statistically rigorous methods.

Paleoclimatic analysis can help to construct a more complete understanding of the hydroclimatic ranges to which water management systems may be exposed. As alluded to earlier, the major Colorado River storages (Lakes Powell and Mead) are large enough to maintain high pool levels during a few dry years, but the extended dry period of the 2000s lowered reservoir pools and streamflows to the extent that power generation dropped by 25–30% for multiple years. The paleo record contains droughts that far exceed the severity of twentieth-century droughts. Most large hydropower systems in the United States and Canada were designed before a widespread appreciation of low-frequency hydroclimatic variability; thus, the extended dry phases of such cycles represent a future capacity risk for many of these systems.

5.12.6.2.4 Climate Change Risk and Associated Hydrologic Uncertainty

Although natural but poorly understood long-memory processes may give rise to apparent trends in short observational records, another possible source of such trends exists. Population and associated economic growth have led to both extensive deforestation worldwide and widespread and intensive use of fossil fuels. The former constitutes reduction in a carbon sink, and the latter amounts to increase in a carbon source. The net effect is to substantially increase the total amount of carbon dioxide and other GHG in the atmosphere. Their transparency to shortwave radiation and opacity to longwave radiation causes a natural 'greenhouse effect' that is essential to life on Earth: the average planetary temperature would be well below the freezing temperature of water without it. In balance, the greenhouse effect supports the Earth's flora and fauna. Multiple lines of observational evidence have converged in recent decades to suggest that increases in GHG from anthropogenic sources since the Industrial Revolution have altered this balance, adding a new forcing to the natural climatic changes that have taken place throughout Earth's history (such as those associated with orbital and solar output variations, as well as geologic processes such as continental drift, mountain building, and erosion, which affect ocean and atmosphere circulation patterns). Anthropogenic climatic changes appear to be much more rapid than changes due to natural variability, possibly presenting greater adaptation challenges to both ecosystems and societies. This section will briefly review how associated hydrologic impacts are assessed, and how they may potentially be manifest in the PNW.

5.12.6.2.5 Methods of Study

Inference about potential anthropogenically forced changes in the hydroclimate follows two primary pathways. The first is to assess geophysical observations describing a broad range of earth system variables, using datasets that include both direct measurements (e.g., ground station air temperature) and proxy records (e.g., from ice cores, lake sediments). The IPCC states that estimated increases in globally averaged temperatures observed since the mid-twentieth century are very likely to be due to anthropogenic GHG increases. The scientific understanding of the effects of this warming on regional hydroclimatic parameters is incomplete, but many researchers have noted the consistency of observed regional warming and hydrologic effects with the concept of a forced climatic change impact that appears to be underway already (e.g., USGCRP 2009; Barnett et al. 2008). As an example, statistical analyses of historical streamflow data in northwestern North America by Fleming and Clarke (2003) and Stahl and Moore (2006) showed how glaciers can affect the long-term responses of rivers to historical climatic changes, and that these phenomena vary by region. Numerous analyses of the twentieth-century hydroclimate in the western United States (described in USGCRP 2009 and in the IPCC reports) have documented changes in glacial extent, seasonal snowpack, and river flows that are consistent with regional warming.

Since the mid-1990s, a second approach for estimating potential anthropogenic climatic change influences on future climate, hydrology, and water resources has involved a sequence of computational models, with the results of one model feeding into the next. The model chain begins with GHG emission scenarios that reflect different assumptions about future global socioeconomic and technological development that will affect emissions. The resulting sets of potential future GHG sequences become inputs (forcings) to GCMs (GCM is now widely used to stand for Global Climate Model, a type of mathematical–computational simulation of the land, ocean, polar ice, and atmospheric components of the global climate system that is normally run on supercomputers by various different climate science groups around the world). The relatively coarse scale output from GCMs (e.g., a 10 000 km^2 grid cell is typical) must be *downscaled* to be useful for watershed studies via either statistical or dynamical methods – the latter uses finer resolution atmospheric model simulations to transfer GCM signals. The downscaled GCM results are then used to drive process-oriented hydrologic models (e.g., Singh and Woolhiser 2002; Beckers et al. 2009; Fleming 2009b), which in turn produce streamflow scenarios that are used in water resources analysis for potential future climates.

The propagation of model uncertainties and errors through such a modeling chain leads to significant uncertainty and potential for misinterpretation in projections of future streamflows and water resources performance. A common means of quantifying the uncertainty is to employ model ensembles (i.e., a large set of GCM simulations of future climates), although most studies to date have not extended the ensemble aspect to downscaling methods or land surface modeling. The resulting distributions of projected hydrographs aim to bracket future hydrologic response uncertainty, while recognizing that this description of uncertainty is nonetheless incomplete. Analysis of climate model-based uncertainty alone (Harding et al. 2012; Deser et al. 2012) suggests that future climate uncertainty has not been captured effectively by the model-based approaches to date.

The combination of statistical analysis of historical data records for climatic trends and hydroclimate sensitivities with model-based hydroclimatic projections (which are in effect sensitivity analyses) provides important context and guidance toward potential future climatic change resource vulnerabilities. Recent hydrological variability and possible trends characterize the sensitivities of watershed systems to warming and variability in precipitation, while projections provide further 'what if?' scenarios with which a wider range of sensitivities can be explored. The following discussion describes findings from this body of analysis.

5.12.6.2.6 Projections for PNW Hydrology and Hydropower

Model-based work on the potential impacts of AGCC on water resources within the PNW as directly relevant to hydroelectric generation has included Whitfield et al. (2002), Stahl et al. (2008), Moore et al. (2011), and Schnorbus et al. (2011) in Canada; in the United States, early work describing Columbia River hydropower impacts included Payne et al. (2004). More recently, federal management agencies have released findings from similar types of studies (such as Reclamation 2011). This work assesses projections of warmer conditions for the future in the PNW and the likely streamflow impacts of such potential changes.

For PNW rivers having a substantial snowmelt component, that is, most rivers in the region except relatively small low-elevation coastal streams, the spring freshet is expected to move forward in time because of warmer temperatures. This shift would likely involve both an earlier onset of the snowmelt freshet and an earlier end. The latter might also contribute to a decrease, on average, in late-summer baseflows. In principle, greater evapotranspiration losses might also occur in late summer in a warmed climate, but the strength of this effect remains unclear. Lower baseflows in glaciated catchments, such as some Columbia River headwater watersheds (contributing energy to the massive hydroelectric complexes along the Columbia River) and various locations along the BC coast (contributing energy to a host of current, planned, or proposed small hydro and/or run-of-river projects), may also be expected as a result of ongoing glacier recession and progressive loss of melt-contributing permanent ice mass.

Warmer temperatures may also contribute to a greater proportion of precipitation falling as rain rather than snow, leading to additional timing effects. For temperate coastal basins exhibiting both winter rainfall and spring snowmelt freshets, such a transition between precipitation types would likely yield a *de facto* transfer of water from the spring freshet to the winter freshet. For colder basins located inland or at higher elevations, where temperatures would be likely to remain well below freezing through most or all of the winter even in a significantly warmed climate, the hydrologic impact of that same transition might be toward higher shoulder-season (late fall–early winter and late winter–early spring) runoff events.

From historical observations, the sensitivity of PNW streamflows to variations in precipitation is relatively clear (e.g., amplified rainfall yields higher streamflow subject to moderation by snowpack dynamics). Climate model projections for precipitation, however, are far less informative than for temperature about the direction of potential future changes. In general, studies suggest (for the PNW) a wetter climate in the mean, an increase in winter precipitation, and a decrease in summer precipitation. Confidence cannot currently be assigned to such regional projections, and indeed, different GCM projections for the PNW vary significantly from substantially drier to substantially wetter potential futures. Furthermore, the decadal phasing of precipitation changes in climate models is largely driven by unforced, thus largely random, internal model-specific variability. This temporal uncertainty, coupled with the general inability of many GCMs to reproduce comprehensively the important features of regional climates, precludes the quantification and even directional indication of precipitation-driven changes in hydrology at a regional level.

Notwithstanding these uncertainties, Figure 10 illustrates possible consequences of warming and precipitation changes for streamflow hydrographs in the PNW. Warming is manifested in the timing shift of runoff toward earlier in the year, and precipitation uncertainty is manifested in the spread of the

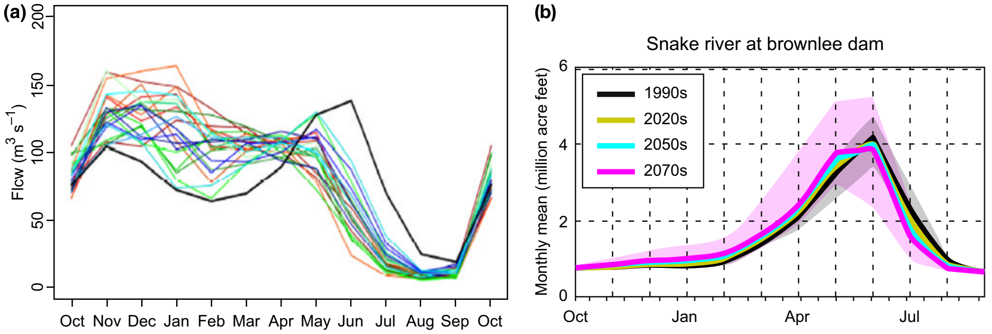

Figure 10 Projected future climatic effects on the Pacific Northwest streamflow. (a) Ensemble of median annual Campbell River hydrographs *c.*2050 (colored lines) and historical value (thick black line) (based on Schnorbus et al. 2011). (b) Simulated future mean-monthly runoff for a tributary to the Columbia River Federal Power System. Reproduced from Bureau of Reclamation, 2011: *West-Wide Climate Risk Assessments: Bias-Corrected and Spatially Downscaled Surface Water Projections*. Bureau of Reclamation, US Department of the Interior.

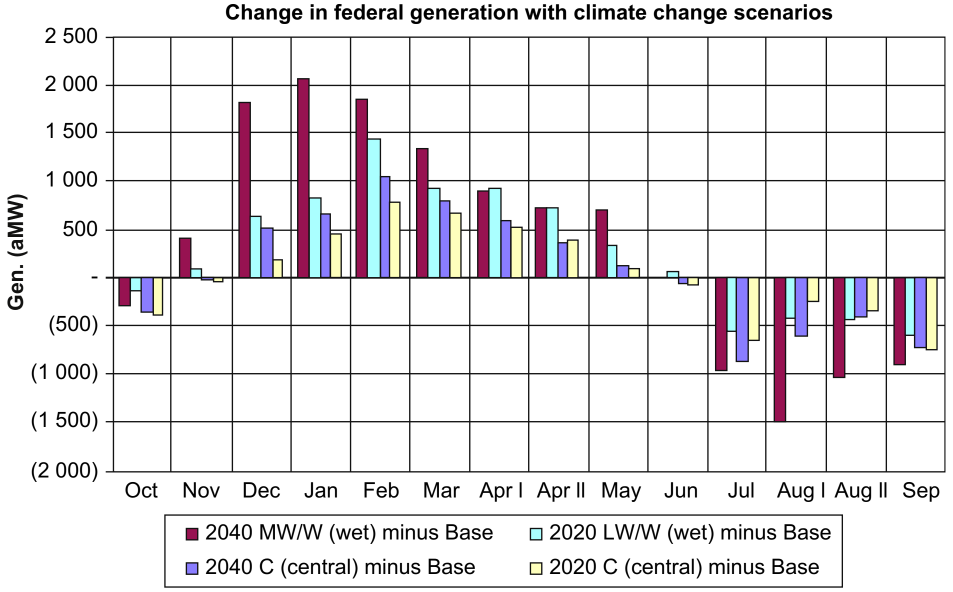

Figure 11 Impacts of projected future climate on hydropower generation in the Columbia River System. Three future climate scenarios – more warming and wetter (MW/W), less warming and wetter (LW/W), and central (C) – for two future periods (2020 and 2040) are compared to a current climate base case. (USACE, BPA, and Reclamation 2011).

projected hydrographs. Both features have been present in nearly all studies of PNW hydrologic sensitivity to climatic variation and potential change, and represent the type of vulnerability now being considered in water sector planning.

A number of studies have carried the hydrologic sensitivity analyses forward into assessments of impacts on power generation. In general, the findings reflect the dominant signals from the hydroclimatic analysis, with hydrograph changes largely determining generation changes. Figure 11, for example, conveys the consequences of the hydrologic changes produced by several climate scenarios (wetter and warmer and a central tendency of the future ensemble) for future hydropower in 2020 and 2040. These scenarios expect more hydropower in winter and less in summer, which is consistent with hydrologic effects. These scenarios are akin to sensitivity studies rather than projection-based assessments in that they show single-valued mean system responses to prescribed changes in climate.

5.12.7 The Sustainability of Hydropower in the Pacific Northwest

By the middle of the twenty-first century, the human population is expected to reach 9 billion. Concern is growing that the activities of our current population are already defining a new era that may earn the label of the 'Anthropocene' because of the unprecedented scale of human society's impacts on the Earth's climate and ocean and terrestrial ecosystems. Although potential exists for the mitigation of these impacts as a result of technological progress and increased adoption of conservative or preservative lifestyles, the evidence of the last half-century suggests a greater likelihood that current practices related to the consumption of energy and material resources are likely to persist for the foreseeable future.

If energy demand grows in proportion to population, the present mixture of energy supply, in which 80% of the Earth's electricity is drawn from thermal fuel sources, may be unsustainable given the attendant climate risk, impacts of energy resource development, and energy security consequences. A transition toward greater reliability on renewable energy development is likely to continue as part of a broader strategy to mitigate climatic impacts while meeting energy needs. The environmental community that has historically opposed hydropower for envirosocial reasons supports the new renewables and a diminishing reliance on fossil fuels. This chapter describes the unique and central role that large-scale hydropower plays as the current major source of utility-scale renewable energy, and perhaps more importantly as an energy storage and backup reserve that facilitates the integration of other intermittent renewables into an energy grid. It suggests that along with energy demand and the need for greater renewable sources, the need for hydropower may also grow, leading to changing roles and opportunities for at least some forms of hydropower development.

Yet, will overall hydropower capacity expand significantly or fall because of other constraints? This chapter has described a broad range of forces and phenomena that have shaped the evolution of North American hydropower during the past century, and that color its current outlook. The prospect of future conventional hydropower capacity growth – particularly at large scales, but even at the upper end of the small scale – is undermined by a number of realities. Foremost is that it collides with firmly established opposition rooted in negative perceptions of the environmental and social consequences of hydropower development, many of which are reflected in the regulatory environment for hydropower development and operation. After technological and engineering advances of the Industrial Revolution engendered an era of hydropower expansion, rising awareness of these issues helped to halt hydropower growth in much of the developed world. Although hydropower continues to grow worldwide, with new plants of all scales being constructed in nations of Asia, South America, and Africa, new additions to large-scale capacity in North America and other developed regions such as Europe would require a sea of change in societal values to enable a permissive overhaul of water, energy, and environmental policies.

If hydropower development in regions such as the US PNW were to awaken, however, growth may yet be undermined by a range of phenomena that resist quantification because of their complexity and the limits of current earth system science. The climate, hydrology, and water management communities now grapple with the possibility that the climate, land use, land cover, and associated hydrologic regimes for which we plan and build may not arrive in the future. Hydropower employs infrastructure and operations, management, and planning conventions that were largely designed with the assumption of stationary hydroclimatological parameters, in particular, those determining streamflow; thus, the performance and viability of a hydropower system may depart from expectations if these parameters are realized in ways that exceed planning and design ranges. The hydropower system consequences could include lowered capacity factors or nonoptimal power operations to mitigate poorly quantified flood risks.

Substantial hydroclimatic measurement uncertainties are associated with low-frequency climatic variability, for example, that attributed to the decadal or longer cycles such as the PDO, and the even less well understood fractal scaling dynamics of long-memory processes in climate and watershed systems. Paleoclimatological reconstructions of streamflow records show that low-frequency variability and long-memory processes do, indeed, place substantial portions of natural variability outside the envelope that can be characterized by modern observing system records, which are typically of less than 100 years in length. Nonstationarity can also arise from long-term landscape change, such as large-scale vegetation change, land-use change, forestry and agricultural practices, and glacier change. This chapter summarizes efforts to assess the further possibility that anthropogenic climatic change may alter climate patterns and the hydrologic regime, leading to capacity risk for new and existing plants. Both retrospective assessments and future projections for the PNW favor warmer and wetter future regimes. These are not without impacts and are preferable to drier futures, but warming impacts on the massive natural reservoir represented by the region's snowpack also carries risk. The outlook for existing and new hydropower is sensitive to these diverse sources of variability and change, and a solid quantitative grasp of these sensitivities will be crucial not only for the resilient operation of existing hydroelectric systems but also for effective planning for tomorrow.

Uncertainties regarding the influence of these various geophysical phenomena translate into uncertainty in the prospects for hydropower in the PNW, but only to a degree. Major and arguably more absolute constraints on hydropower development and growth continue to stem from societal values and perceptions that oppose hydropower at large scales required to contribute substantially to a renewable energy in future and thereby mitigate continued growth in energy industry carbon emissions. Despite pressure toward greater acceptance for hydropower (as views on the sustainability and impacts of thermal generation darken and hydropower's role in firming renewable sources is defined), the landscape of PNW hydropower appears likely to evolve modestly at best during the twenty-first century. The United States has developed only 20% of its estimated hydropower potential, and only 2400 of 80 000 dams are powered. Upgrades that add power to existing dams and also new small-scale, pumped storage and hydrokinetic generation will increase overall capacity to some extent.

Over the next century, if opposition to large-scale hydropower does not weaken, the evolution of the US hydropower capacity will reflect a balance between this development and any large-scale hydropower losses – deratings or decommissionings (e.g., as dams fill with sediment, weaken, and become unsafe to operate at present capacity or experience runoff changes for which they cannot effectively reoperate). Rivers will not cease to flow downhill in a region where abundant precipitation falls in the mountains, thus the sustainability of PNW hydropower will to a greater extent be determined by the energy and environmental policy that the society adopts in the future.

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Disclaimer

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5.13 Water Resources of Mainland China

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5.13.1 Introduction

Mainland China has a total terrestrial area of 9.6 million km^2, with a large range of both latitude and longitude. Its topography is characterized by high elevation in the southwest in association with the Qinghai–Tibetan Plateau and low altitude in the east (see Figure 1). Large areas in eastern and southern China are affected by oceanic air currents in summer and by continental air currents in winter, resulting in dry winters and wet summers. Because of geographic and climatic factors, China is vulnerable to severe floods and droughts.

The average annual precipitation in China (see Figure 2) is 650 mm year^{-1} (i.e., 6177.5 billion m^3 year^{-1} in total), which is less than the world land surface average of 800 mm year^{-1}; moreover, the spatial and temporal variations of precipitation are large (Ministry of Water Resources of China 2009). Generally, the precipitation decreases from the southeast coast, with 1800 mm year^{-1}, to the northwest inland, with 50 mm year^{-1} (Figure 2), while the Himalayan Mountains in the southwest are associated with high precipitation. The wet season in southern China lasts from April to September; in the north, it lasts from June to September. The range of the ratios of annual rainfall between a wet year and a dry year for different regions is 2–8, and sequences or clusters of the wet or dry years do occur (Ministry of Water Resources of China 2009).

The total water resources in China amount to approximately 2800 billion m^3 year^{-1}, which accounts for 6% of the world total water resources; the volume of water resources in China ranks sixth in the world, after Brazil, Russia, Canada, USA, and Indonesia (Ministry of Water Resources of China 2009). However, since the population of China reached 1.37 billion in 2010, the average amount of water resources per capita is 2100 m^3 year^{-1} (see Figure 3), which is less than one-third of the world average; this number ranks 121st in the world. Therefore,

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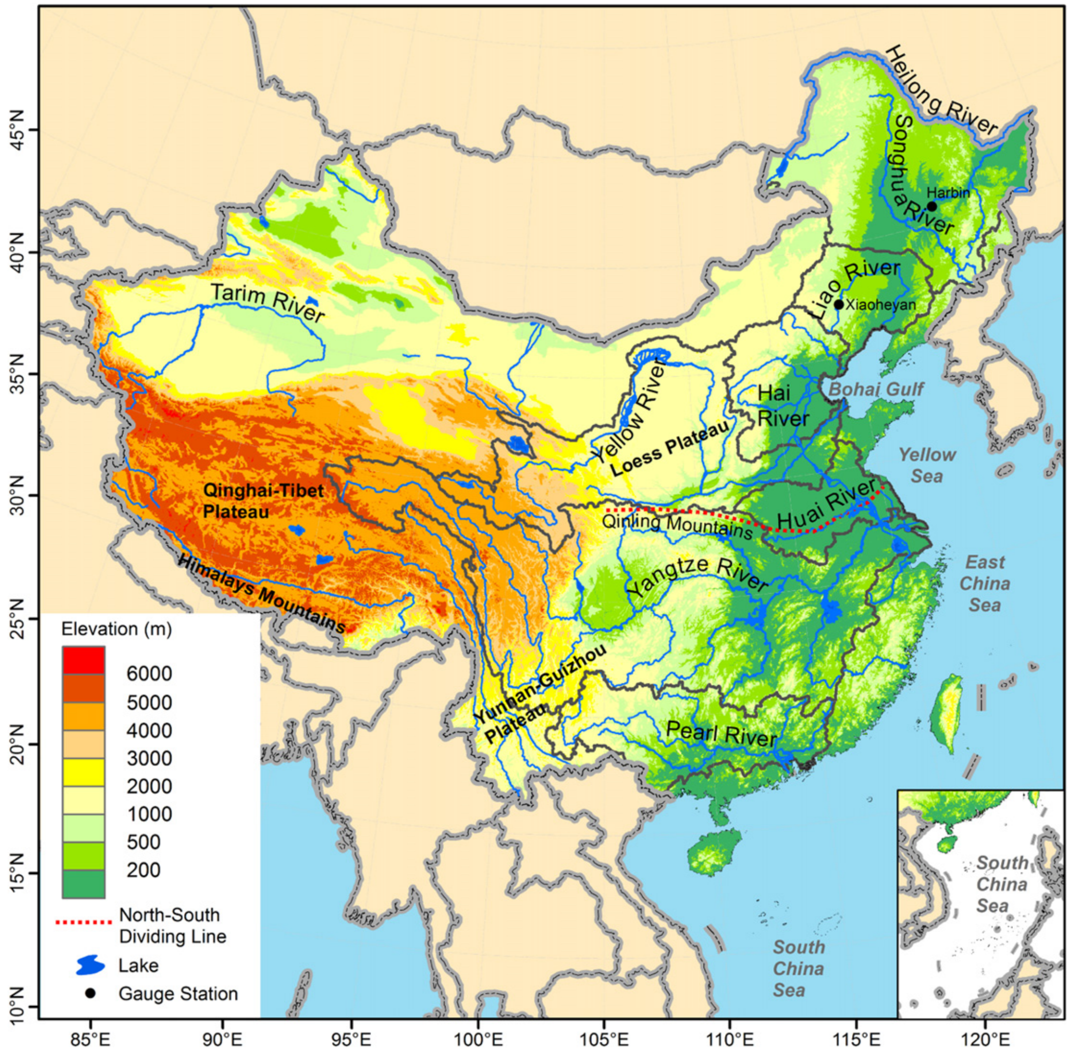
45°N
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110°E
115°E
120°E
Heilong River
Songhua River
Harbin
Liao River
Xiaoheyan
Tarim River
Yellow River
Hai River
Bohai Gulf
Loess Plateau
Yellow Sea
Qinghai-Tibet Plateau
Qinling Mountains
Huai River
Himalays Mountains
Yangtze River
East China Sea
Yunnan-Guizhou Plateau
Pearl River
South China Sea
South China Sea
Elevation (m)
6000
5000
4000
3000
2000
1000
500
200
North-South Dividing Line
Lake
Gauge Station

Figure 1 Geographic location of China and major river basins.

China has one of the lowest averages of water resources per capita in the world (Ministry of Water Resources of China 2009). Of the annual runoff (2738.8 billion m^3 $year^{-1}$), the minimum basic flow needed for the support of river ecosystems is approximately 867 billion m^3 $year^{-1}$, while flood water (which cannot be used as a water resource) accounts for 1051 billion m^3 $year^{-1}$; hence, the maximum usable volume of water in mainland China is approximately 882 billion m^3 $year^{-1}$, which is 28% of the annual runoff (Wang 2007, 2010).

In mainland China, water resources are unevenly distributed spatially and seasonally. The Qinling Mountains–Huai River line is generally regarded as the geographical dividing line between South and North China (see Figure 1). The average water resources are 560 billion m^3 $year^{-1}$ (1100 m^3 $year^{-1}$ per capita) in South China (including the Yangtze River, the Pearl River, Southeast River basins, and Southwest River basins), and 204.5 billion m^3 $year^{-1}$ (359 m^3 $year^{-1}$ per capita) in North China (including the Songhua River, the Liao River, the Hai River, the Yellow River, and the Huai River); the south is comparatively water rich.

Along with economic development, population growth is the dominant driving force for water demand increase. Figure 4 shows the change in national population and gross domestic product (GDP) in mainland China (National Bureau of Statistics of China 2011) from 1950 to 2010. It is worth noting that the population growth rate in the central and western regions of China is faster than the eastern region for the period from 1978 to 2003 (National Population and Family Planning Commission of China 2007). In 2006, water supply in China was 579.5 billion m^3, with surface water accounting for 81.2% and groundwater 18.4%, respectively (Ministry of Water Resources of China 2006). This was 5.5 times the water consumed in 1949, with an annual increase of approximately 3% over the period from 1949 to 2006. Moreover, in 2007, the amount of water resources per capita was 2156 m^3 $year^{-1}$; this number is expected to decline to 1875 m^3 $year^{-1}$ per capita when the projected peak population reaches 1.5 billion around 2033 (Xie et al. 2009).

Figure 5 shows the categories of water use in 1999 (Ministry of Water Resources of China 1999) and 2008 (Ministry of

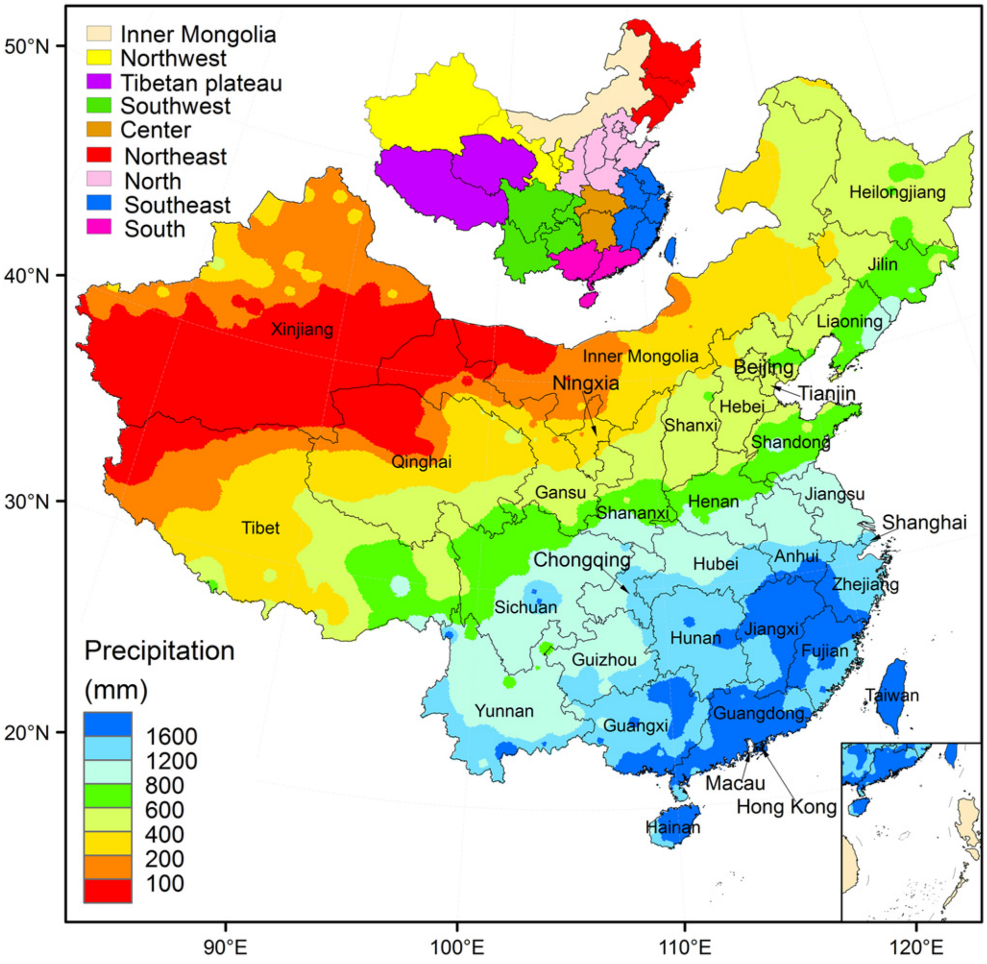
Inner Mongolia
Northwest
Tibetan plateau
Southwest
Center
Northeast
North
Southeast
South
Precipitation (mm)
1600
1200
800
600
400
200
100
Heilongjiang
Jilin
Liaoning
Xinjiang
Inner Mongolia
Beijing
Tianjin
Hebei
Ningxia
Shanxi
Shandong
Qinghai
Gansu
Henan
Jiangsu
Shanghai
Shananxi
Tibet
Chongqing
Hubei
Anhui
Zhejiang
Sichuan
Jiangxi
Hunan
Fujian
Guizhou
Taiwan
Yunnan
Guangdong
Guangxi
Macau
Hong Kong
Hainan
50°N
40°N
30°N
20°N
90°E
100°E
110°E
120°E

Figure 2 Major districts of China and spatial distribution of annual average precipitation.

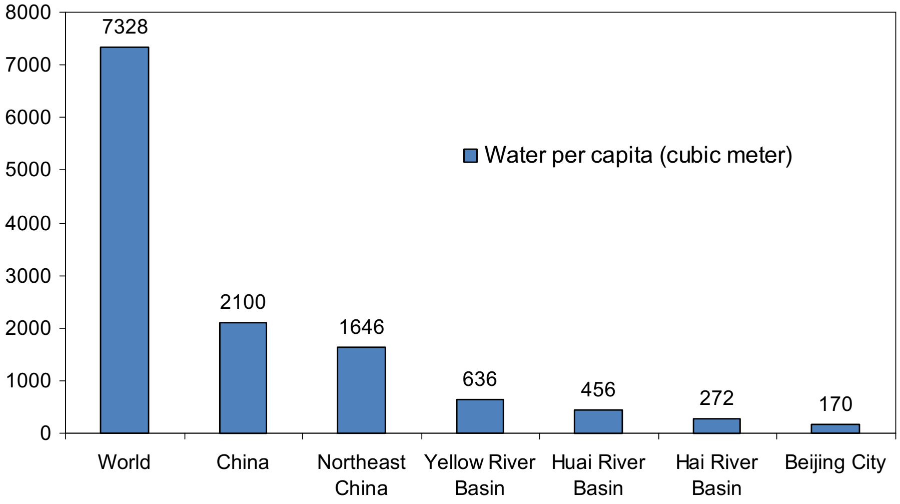

Figure 3 Water resources per capita in the world and mainland China in 2006. Adapted from Wang, H., 2010: *Water Resources Callenges and Policies in China*. Public Lecture, Hong Kong.

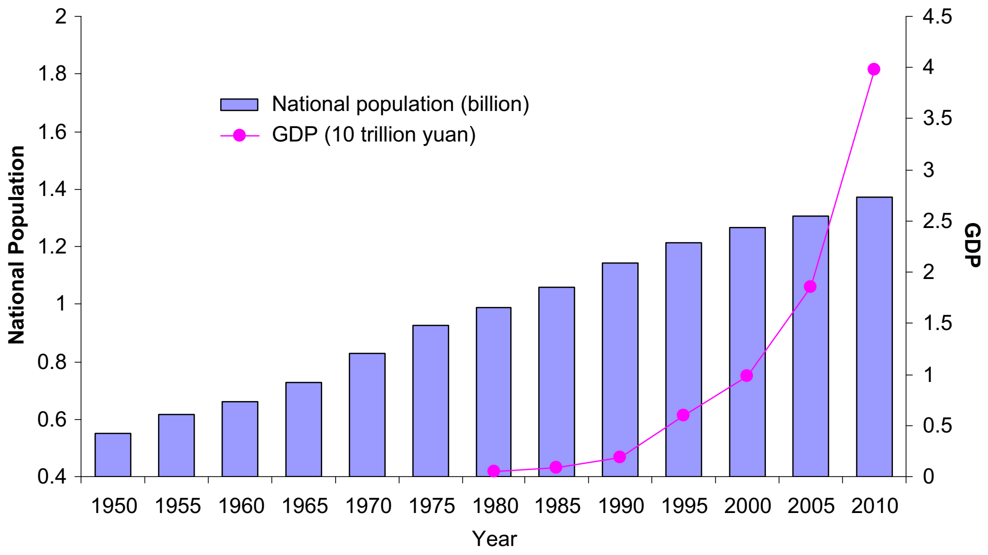

Figure 4 National populations and GDP from 1950 to 2010 in mainland China. Adapted from National Bureau of Statistics of China, 2011: *China Statistic Yearbook*. China Statistics Press.

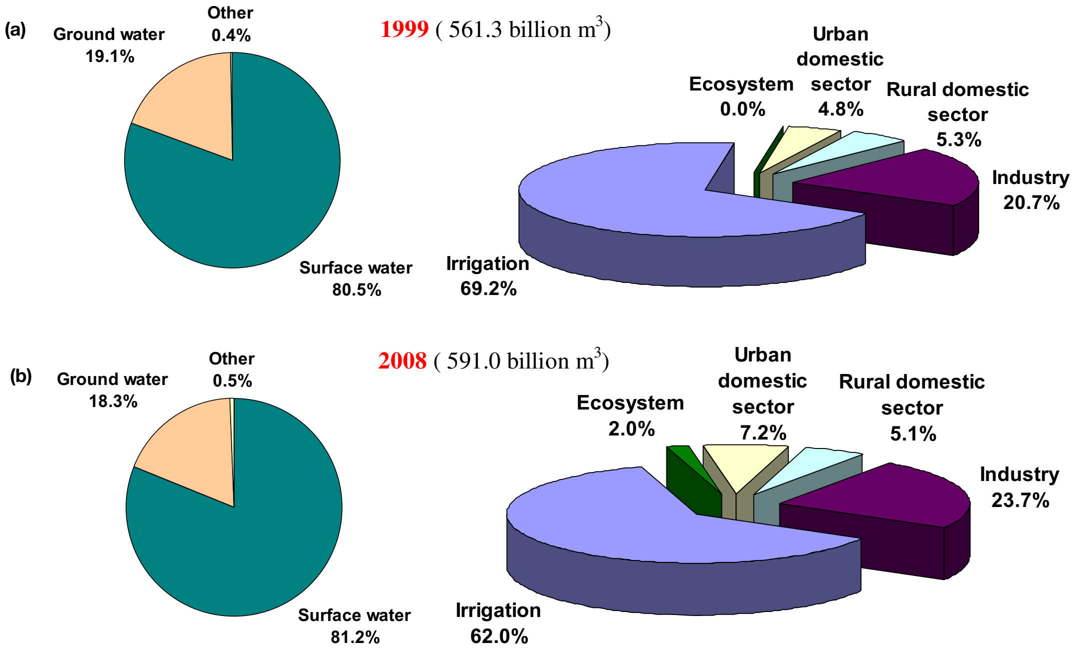

Figure 5 Sources of water supply (left panel) and water use by different sectors (right panel) in mainland China in (a) 1999 and (b) 2008.

Water Resources of China 2008). In both years, irrigation accounts for more than 60% of use; industry is the second largest user and accounts for more than 20% of water used. The ratios of water use for urban domestic and industry sectors in 2008 are 3% larger than those in 1999. Therefore, urbanization has become another factor driving the water demand increase; it is expected that the urban domestic water demand will further increase because the urban population will reach 55–66% of total national population by 2020 (Xie et al. 2009). The continuous growth of China's population and economy, leading to higher water demand and associated water-related environmental issues, makes the study of water resource vulnerability extremely important. The possibility of further changes in climate provides a further imperative of exploring and understanding the characteristics of water resources in mainland China.

5.13.2 Water Resource Status in Seven River Basins

There are more than 50 000 rivers in China with drainage basin areas larger than 100 km^2; of these, more than 1500 have basin

Table 1 The seven major rivers in mainland China (Qian 1994)

River	*Length (km)*	*Basin area (km^2)*	*River's destination*	*Population in 2004 or 2005 (millions)*
Yangtze River	6397	1 808 500	East China Sea	440
Yellow River	5464	752 443	Bohai Gulf	113
Songhua River	2308	557 180	Heilong River	62
Pearl River	2214	453 690	South China Sea	99
Huai River	1000	269 283	Yangtze River and Yellow Sea	172
Hai River	1090	263 631	Bohai Gulf	130
Liao River	1345	228 960	Bohai Gulf	35

areas larger than 1000 km^2. Most rivers in China are fed by rainfall, and some rivers are partly fed by snow or glacier melting water. The seven major rivers in mainland China are the Yangtze River, the Yellow River, the Songhua River, the Pearl River, the Huai River, the Hai River, and the Liao River (see **Figure 1**). **Table 1** lists the basic hydrological information of these seven river basins. Note that city names, river gauge station names, and dam names given in the following text are marked in **Figures 1 and 9–11**.

The total area of the seven major river basins (the Yangtze River, the Yellow River, the Songhua River, the Pearl River, the Huai River, the Hai River, and the Liao River) is approximately 45% of the total land area of mainland China (see **Figure 1**). However, the volume of water resources of these basins is approximately 64% of the country's total, with approximately 80% of the total population living there. **Table 2** lists the basic information on the water resource status of these seven river basins; the amounts of annual water resources per capita are calculated based on the population in 2004 for the Pearl River basin and 2005 for other six basins. The threats of water shortage over the Hai River, the Huai River, and the Yellow River basins are obvious (**Table 2**). The following sections briefly introduce the seven river basins one by one.

5.13.2.1 Yangtze River

The Yangtze River is the largest river (in terms of the length, basin area, and streamflow volume; see **Table 1**) in China and the third longest river in the world. The basin area is 1.8 million km^2 and the length of the mainstem is 6397 km. The Yangtze River basin runs through 19 provinces (including autonomous regions and municipalities), namely Qinghai, Tibet, Sichuan, Gansu, Shaanxi, Yunnan, Chongqing, Guizhou, Guangxi, Guangdong, Hubei, Hunan, Henan, Anhui, Jiangxi, Zhejiang, Fujian, Jiangsu, and Shanghai (see **Figures 1 and 2**). There are many tributaries, such as the Min River, the Wu River, the Xiang River, the Han River, the Huangpu River, and so on; among them, the Han River is the longest one. The Qutang Gorge, Wuxia Gorge, and Xiling Gorge of the river are known as the Three Gorges (*Sanxia* in Chinese). The population over the basin reached 0.44 billion in 2005, which is more than 30% of the total national population of China. The river basin is located mainly in subtropical climate zones, and seasonal and interannual variations of the runoff in the mainstem are large. As an agricultural production base, the rice product in the basin accounts for up to 70% of the total in China. The potential hydropower capacity of the river reaches 250 000 Million Watts (MW). The river has abundant fish resources, with about 500 fish species. Consequently, the water resources in the Yangtze River basin make a great contribution to the agricultural and economic development in mainland China.

The streamflow of the Yangtze River is relatively stable (Lu 2004). Nevertheless, the Yangtze River basin is vulnerable to floods and droughts, especially in its middle stream and downstream regions. For example, a serious flood that occurred in 1998 over the entire river basin submerged an area of more than 0.2 million km^2 and caused an economic loss of 166 billion RMB Yuan (about US$ 20 billion in 1998 equivalent) (Yin and Li 2001). The drought that occurred in 2011 in the middle and lower reaches of the river was the worst since 1961; the economic loss due to the 2011 drought was 14.9 billion RMB Yuan (about US$ 2.3 billion in 2011 equivalent), and the farmland affected totaled 40 000 km^2.

5.13.2.2 Yellow River

The Yellow River is the second largest river in terms of both the basin area (752 443 km^2) and length (5464 km) in China. The river runs through Qinghai, Gansu, Sichuan, Ningxia, Inner Mongolia, Shanxi, Shaanxi, Henan, and Shandong provinces

Table 2 Status of water resources in the seven major river basins (Qian 1994)

	Annual precipitation		*Annual river runoff*				
River	*Amount (km^3 year^{-1})*	*Depth (mm year^{-1})*	*Amount (km^3 year^{-1})*	*Depth (mm year^{-1})*	*Annual groundwater (km^3 year^{-1})*	*Annual total water resources (km^3 year^{-1})*	*Annual water resources (m^3 year^{-1}) per capita*
Yangtze	1936	1071	951	526	246	961	2181
Yellow	369	464	66	83	41	74	655
Songhua	279	500	74	133	12	88	1419
Pearl	897	1544	336	741	112	471	4758
Huai	283	860	74	225	39	96	558
Hai	178	560	29	91	27	42	323
Liao	190	551	49	141	19	58	1657

(see **Figures 1 and 2**). The population in 2005 over the basin was about 0.113 billion. The river is well known worldwide due to soil erosion and sediment problems. Most of the river streamflow comes from upstream Lanzhou City. The runoff yield decreases downstream from Lanzhou City to Hekouzhen station due to the evaporation and leakage losses. The runoff yield increases in the region from Hekouzhen station to Taohuayuan station. However, from Huayuankou station to the river outlet, there are significant water losses along the river channel; the river bed in this part is higher than the surrounding land surface, resulting in a so-called suspended river. This suspended river raises the vulnerability of the region to floods.

In 1958, the river reach between Sanmenxia and Huayuankou stations experienced the worst flood since 1919; the Beijing–Guangzhou railway, which is the main transport route in mainland China, was interrupted for 14 days. In addition, based on the historical records, the Huayuankou station for the period of 1946–88 and the Sanmenxia station for the period of 1953–88 experienced decreasing trends of the annual mean and annual maximum discharge (Lu 2004). On the other hand, because the western and northern parts of the river are located in arid and semi-arid areas, where the annual rainfall is less than 250 mm year^{-1}, basinwide droughts are easily triggered. Furthermore, for the period of 1972–97, the downstream area of the river suffered from dried-up river courses; in 1997, such a situation lasted 226 days, and the annual economic loss was more than 1.1 billion RMB Yuan (about US$ 0.13 billion in 1997 equivalent). This dry situation also brought many other environmental and ecological problems, such as land desertification, aquatic ecosystem stress, water quality degradation, and so on.

5.13.2.3 Songhua River

The source of the Songhua River is the Tianchi Lake on Changbai Mountain. The basin area is 557 180 km^2, and the length is 2308 km (**Table 2**). The population over the basin was 62 million in 2005. As it is located at the mid-temperate climate zone, evapotranspiration is relatively low. The Songhua River at Harbin station experienced an increasing trend of the annual minimum discharge for the period of 1898–1987 (Lu 2004). Since 1950, floods have occurred in 1953, 1956, 1957, 1960, 1969, and 1998. For the 1957 flood, high-intensity rainfalls occurred in July and August, and the number of days with continuous rainfall reached 45. About 4 million people were affected and 81 people died. The economic loss was 0.24 billion RMB Yuan (about US$ 0.1 billion in 1957 equivalent). In 1998, the river experienced another serious flood; the maximum water level reached 120.89 m and the associated discharge was 16 600 $\text{m}^3\,\text{s}^{-1}$ at Harbin station on August 22. For the basin, this flood was the worst in the twentieth century. On the other hand, during the period of 2000–03, the mainstem of the Songhua River endured severe low water levels (the lowest being 110.07 m at Harbin station), and the droughts resulted in the reduction of industrial and agricultural outputs.

5.13.2.4 Pearl River

The total basin area of the Pearl River is 453 690 km^2 (part of the river basin, 11 590 km^2, is located in Vietnam), and the length of the mainstem is 2214 km. The population over the basin was 99.35 million in 2004. The Pearl River is situated in a tropical to subtropical monsoon climate region. The average runoff is 336 $\text{km}^3\,\text{year}^{-1}$, making it the second largest river in terms of streamflow volume in China; the annual runoff generation rate (about $0.74 \times 10^6\,\text{m}^3\,\text{year}^{-1}$) is the highest among the seven major rivers in China. A decreasing trend has been identified for annual minimum discharge at Wuzhou station for the period of 1915–84 (Lu 2004).

Historically, the basin has suffered from frequent floods and most of the river's major tributaries have experienced severe floods (e.g., 1979 flood in the East River, 1982 flood in the North River, and 1998 flood in the West River); serious basinwide floods also occurred in 1915, 1968, 1994, and 2005. For the period of 1990–2005, the total economic loss over the basin caused by floods reached 345 billion RMB Yuan (about US$ 41.7 billion in 1998 equivalent). Droughts also frequently occur over the basin, especially for the southwest region (e.g., severe droughts occurred in 1963 and 2010). In addition, due to the droughts, persistent seawater intrusion has threatened freshwater supply in the Pearl River delta.

5.13.2.5 Huai River

The Huai River basin area is 269 283 km^2, and the mainstem length is 1000 km. The Huai River runs through Henan, Hubei, Anhui, Shandong, and Jiangsu provinces (**Figures 1 and 2**). The river in the lower reach has three branches. One enters into the Yangtze River at Sanjiangying station near Yangzhou City in Jiangsu province; another enters into the Yellow Sea through the North Jiangsu Irrigation Canal; the third one flows into Haizhou Bay through the Huaishu River (a comprehensive water resource utilization project). The total population over the basin was 0.172 billion in 2005. The average population density is about 639 per km^2, ranking first among the seven major river basins in China (Huai 2011). The Huai River at Bengbu station showed a decreasing trend in the annual minimum discharge for the period of 1915–86 (Lu 2004). Due to the significantly changed geography of the Huai River basin in history, water flow in the middle stream cannot easily flow into the downstream region.

Water-related hazards, such as floods and droughts, have frequently occurred in the basin. From 450 CE (Common Era) to 1950, on average, there were 94 floods per century over the basin; droughts occurred 260 times, with a frequency of 1 per 1.7 years (Hai 2011). In the 1991 flood, the area of farmland inundated was 55 160 km^2, and the population affected was 54.23 million. The economic loss in 1991 was 34 billion RMB Yuan (about US$ 6.39 billion in 1991 equivalent). Two severe droughts occurred in 1966 and 1978, associated with an annual average rainfall of 579 mm and 601 mm, respectively, compared to 911 mm year^{-1} for the long-term average; the area affected by each of the droughts was about 33 330 km^2.

5.13.2.6 Hai River

The basin area of the Hai River is 263 631 km^2, with the length of mainstem of 1090 km. It is located in semi-arid and semi-humid areas. There are 25 large- and medium-scale cities in the basin, including Beijing and Tianjin, and the total population over the basin reached 0.13 billion in 2005. The average population density is about 410 per km^2 (Hai 2011). The streamflow volume has greatly decreased since 1980. Due to the serious overexploitation of groundwater, large-scale land subsidence has occurred in the downstream area of the basin. Also, many tributaries are dry for most of the year. Meanwhile, water pollution has worsened in conjunction with the reduced streamflow.

5.13.2.7 Liao River

The Liao River has a basin area of 228 960 km^2, and a mainstem length of 1345 km. The total population over the basin was 35 million in 2005. The basin area and annual runoff (14.8 km^3 year^{-1}) are the smallest among the seven major rivers in China. The Liao River has a high sediment load because many parts of the river flow through powdery loess, which is ranked third behind the Yellow River and Hai River. A decreasing trend of annual mean discharge has been observed at Xiaoheyan station in the Liao River for the period of 1955–98 (Ren et al. 2002). During the past 100 years, 50 floods occurred over the basin; drought events occurred almost every year in the east of the basin (i.e., the Xiliao River basin). In the 2005 flood, 1.34 million people were affected and 1400 km^2 of farmland was inundated; the economic loss was 7.4 billion RMB Yuan (about US$ 0.92 billion in 2005 equivalent).

5.13.3 Some Key Water Resource Issues

Since 1949, more than 51 extreme floods and 18 widespread and severe droughts have occurred in mainland China. Floods and droughts in China are high frequency, with large spatial extent as well as heavy losses of life and societal property. Specifically, the Yellow River delta, the Yangtze River delta, and the Pearl River delta are vulnerable to storm surge, seawater intrusion, coastal flooding, shoreline erosion, and loss of wetlands. Other water resource issues in mainland China include water environment deterioration, soil erosion, river sedimentation, and groundwater overdraft. In the previous section, some water resource issues in the seven major river basins were introduced. The following sections will review some key water-related issues in mainland China.

5.13.3.1 Floods

Floods are one of the most serious disasters frequently occurring in China. Due to the great variation in meteorological, topographical, and geological features over the territory, about two-thirds of the land area of China is subjected to different types of floods. Table 3 lists the distribution features of historical floods in mainland China.

The continental monsoon climate influences most of China. Rainfall in the territory is mainly formed by two types of weather systems (Qian 1994). The first is the westerlies rain belt system, including fronts, extratropical cyclones, tangential lines, and low vortexes. The other is the low-latitude tropical weather system, which includes mostly tropical cyclones and typhoons. The principal source of flood disasters in China is rainstorm floods; other types of floods include snow melt floods, glacier ice melt floods, and the floods caused by storm surges in coastal regions.

Table 3 Statistical information of floods occurring in the period of 1840–1949 (Flood Control and Drought Relief Headquarters, and Nanjing Research Institute of Hydrology and Water Resources (FCDRH and NJRIHWR) 1997)

Spatial coverage	*Number of years*	*Percentage %*
Whole country	4	3.6
North and south	6	5.5
Central	25	22.7
North	15	13.6
South	1	1.0
Other regions	59	53.6
Total	110	100

Generally, in mainland China, flood disasters in the eastern region are mainly caused by rainstorms and coastal storm surges. The western region is primarily subject to mixed-type floods from snow and glacier melting and local rainstorms. The economically developed eastern and southern parts (see Figure 2), which possess approximately 35% of the national cultivated land, 70% of the national agricultural and industrial products, and more than 50% of the national population, are most seriously threatened by floods (Wang 2010).

The total loss caused by floods in China was approximately 1.5% of the GDP for the period of 1990–2010 (Liu 2009). For example, in 1998, 4185 people lost their lives in mainland China due to the unusually high rainfall in the wet season (World Socialist 2005). In 2005, 1660 people were killed in the flood season (National Bureau of Statistics of China 2006). In 2007, 177 million people were affected by the nationwide floods, resulting in more than 1200 deaths, 0.12 million km^2 of croplands ruined, and more than 1 million houses destroyed; the direct economic loss was over 100 billion RMB Yuan (US$ 12.82 billion in 2007 equivalent) (National Bureau of Statistics of China 2008).

5.13.3.2 Droughts

In normal years, due to huge water demands from various water consumption sectors in mainland China, water shortage is 25 billion m^3, accounting for 4% of the national total demand. In dry years, the water shortage can reach 30–40 billion m^3, which is 6% of the total demand. Three-quarters of the national water shortage occurs in North China, and the region with the worst water shortage is the Hai River basin. In the Hai River basin, the situation has been deteriorating since the 1950s, becoming severe since 1980 as reflected in the record of annual runoff (see Figure 6).

The total loss resulting from drought disasters in mainland China was about 1% of the GDP for the period of 1990–2010, or about 300 billion RMB Yuan (about US$ 36.23 billion in 2000 equivalent) (The Ministry of Water Resources 2010). Table 4 lists the statistical information (Flood Control and Drought Relief Headquarters, and Nanjing Research Institute of Hydrology and Water Resources (FCDRH and NJRIHWR) 1997) of drought disasters on agriculture in different river basins; it shows that the drought-influenced areas and drought-resulted damages in the basins of the northern region are normally much higher than in the Pearl River in the southern region. During the periods of 1949–90 and 1971–90, the

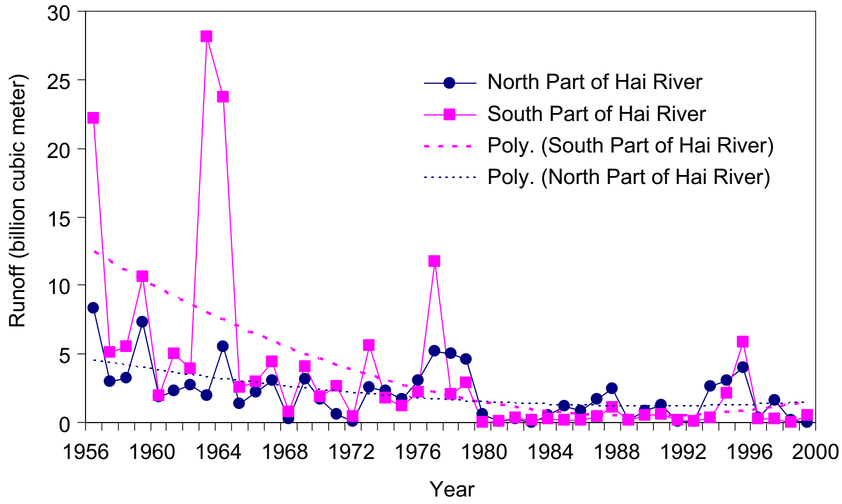

Figure 6 Annual runoff variations in the Hai River. Adapted from Shen, D. J., 2010: Climate change and water resources: evidence and estimate in China. *Curr. Sci.*, **98**, 8.

highest drought impact in northern China occurred in the Yellow River basin, followed in decreasing order by the Songhua River, the Liao River, the Huai River, and the Hai River (FCDRH and NJRIHWR, 1997).

In 2010, southwest China (including Yunnan, Sichuan, and Guizhou provinces, Guangxi Zhuang autonomous region, and Chongqing municipality) suffered from the worst drought in six decades; it lasted 6 months and resulted in serious drinking water shortages and crop damages. According to statistics from the China Foundation for Poverty Alleviation (CFPA), the direct economic loss of the drought was more than 35 billion RMB Yuan (about US$ 5.12 billion in 2010 equivalent), and more than 2 million people were reduced to poverty levels. The drought affected about 5000 km^2 of natural reserves, and shrinking wetlands and water shortages for wildlife were reported by the Yunnan provincial forestry bureau (China Daily 2010). In 2011, the worst drought in 50 years hit the midstream and downstream areas of the Yangtze River basin. Precipitation in the regions (including the Anhui, Jiangsu, Hubei, Hunan, Jiangxi, and Zhejiang provinces and Shanghai municipality) was 30–80% less than that in normal years. The surface area of the largest freshwater lake in mainland China, Poyang Lake in Jiangxi province, shrank to just 16% of its average.

The difference between areas of cropland damaged (referring to where the crop production is reduced by more than 30%) and areas of agriculture affected (referring to where crop production is reduced by more than 10%) by droughts depends not only on the variation of meteorological conditions, but also the irrigation efficiency and the irrigation intensity of farmlands. The ratio of cropland damaged to total agriculture area affected in northern China is more than 0.5, while the ratio in the Pearl River basin in the southern China is less than 0.4 (FCDRH and NJRIHWR 1997). Moreover, Ge et al. (2011) estimated the water footprint for each province (or autonomous region) in mainland China, in which the water footprint is defined as the total volume of freshwater consumed for producing the goods and services (Hoekstra et al. 2009). With reference to the water footprint, the extent of water shortage in Tianjin, Beijing, and Shanghai municipalities, Ningxia autonomous region, and Hebei and Shanxi provinces are the worst in mainland China.

5.13.3.3 Soil Erosion

Soil erosion is an important factor in influencing river sedimentation and water quality. The total eroded area in China amounts to one-sixth of the territory (Qian 1994). A large amount of fertile soil from farmlands is eroded and transported into the rivers and seas. The eroded areas are mainly found in the Loess Plateau in North China, the Yunnan–Guizhou

Table 4 Droughts over the major river basins (FCDRH and NJRIHWR 1997)

	Average during 1949–90			*Agriculture affected rate*		*Crop damaged rate*	
River basin	*Agriculture affected rate (%)*	*Crop damaged rate (%)*	*Crop extinction rate (%)*	*Max (%)*	*Year*	*Max (%)*	*Year*
Songhua and Liao	12.3	7.1	0.7	54.2	1982	41.8	1989
Hai	9.9	6.5	0.5	30.6	1965	18.3	1986
Huai	10.7	5.6	0.3	33.9	1978	22.8	1988
Yellow	16.2	11.3	1.5	33.6	1987	27.0	1987
Yangtze	10.3	5.6	0.8	26.1	1959	15.7	1978
Pearl	9.6	4.0	0.8	26.1	1988	18.6	1963

Plateau in southwest China, and the hilly and mountainous regions in South China (Figure 2). The area of the Loess Plateau is 340 000 km^2 with an annual precipitation ranging from 300 to 600 mm year^{-1}. Within the loess area, the gullied plateau regions and the gullied-hilly regions, amounting to 250 000 km^2, have the highest erosion rates. Due to the high storm intensity, sparse vegetation cover, and steep slopes, soil erosion in the Loess Plateau is rampant and results in a distinctive geomorphological landscape (Qian 1994). The erosion rate ranges from 5000 to 10 000 t km^{-2} year^{-1} on slopes and from 15 000 to 20 000 t km^{-2} year^{-1} in gullies. The Karst region of the Yunnan–Guizhou plateau with an eroded area of about 340 000 km^2 is another region of extensive erosion, and it has an annual precipitation of 1000 mm year^{-1}.

Eroded areas account for about 54% of the Yellow River basin, with a normal surface area erosion rate of 2500 t km^{-2} year^{-1}. Based on sediment transport observations, the most seriously eroded area in the Loess Plateau has an erosion rate of 5000–8000 t km^{-2} year^{-1}, which is the highest in China and the main source area for sediment in the Yellow River basin. In the Yangtze River basin, the eroded area is about 570 000 km^2, and the annual soil loss is about 3500 to 4000 t km^{-2} year^{-1}. The region of most serious erosion is in the upper stream of the Yangtze River, from Dukou City to Yichang City. The eroded areas in the Hai River, the Huai River, the Songhua River, and the Liao River basins are about 104 000 km^2, 56 000 km^2, 180 000 km^2, 128 000 km^2, and 59 000 km^2, respectively. Overall, soil erosion is a serious issue in sustaining water resource security in mainland China, and measures for protecting the land surface and preventing soil erosion are necessary. To this end, there are numerous engineering projects implemented in mainland China. For example, the Grain-for-Green project for western China took off in 2000; the project aims to turn low-yielding farmland back into forest and pasture to reduce soil erosion and restore ecological balance in the western region.

5.13.3.4 River Sedimentation

Over 40 rivers in China carry a large amount of sediment due to severe soil erosion, and each of them has an annual sediment load of over 10 million t year^{-1}. Data for the seven major rivers and some other rivers in southwest China and inland rivers (Qian 1994) reveal that the average annual sediment load totals 2.687 billion t year^{-1}. The main sediment problems include reservoir sedimentation, sediment at low water head hydro projects and in canal systems, sediment in rivers and lakes, sedimentation in estuaries and below tidal barriers, and abrasion of high-energy particle turbines and hydraulic structures by sediment particles.

The annual sediment load transported by the Yellow River is about 1.6 billion t year^{-1}, and the riverbeds in the downstream areas are raised at a rate of 0.06–0.10 m year^{-1} due to the huge amount of sediment (Qian 1994). This threatens the river bank safety during the flood season. Above the Hekouzhen station, the catchment area is 360 000 km^2, and the sediment yield accounts for 9% of the total, while the runoff yield accounts for 53% of the total. The area between Hekouzhen and Longmen stations is 130 000 km^2, and the runoff yield is about 15% of the total, while the sediment yield can reach up to 56% of the river total sediments; it is this area that is the main sediment source in the Yellow River basin.

5.13.3.5 Water Quality

Of the 20 most seriously water-polluted cities in the world, 16 are located in mainland China. Most of the major river basins suffer from severe pollution (Gleick et al. 2008), and about 300 million people have no access to safe water. Table 5 lists the growth rates of water use for the industrial and urban domestic sectors in China since the 1980s. The increase of water use can reflect the growth of wastewater discharge and water pollution.

The main features of the water pollution in China are a large volume of wastewater discharge, little treatment, and an increasing trend of pollution. During the period of 1980–2000, the growth rates of wastewater discharge from the domestic sector and industry were 7.1% per year and 5.3% per year, respectively (Wang 2010). In 2006, the wastewater discharge was about 74.1 billion m^3 year^{-1}, while the treatment rate was 57% in urban areas and only 23% in rural areas. In 2010, the chemical oxygen demand loading to rivers was 30.29 million t year^{-1}; NH_3-N, total nitrogen, and total phosphorus in mainland China discharged into rivers amounted to 1.73, 4.73, and 0.42 million t year^{-1}, respectively (National Bureau of Statistics of China 2010).

Following the Chinese National standard for grading water quality, Grades I, II, and III of water are potable and Grades IV and V are acceptable for use by industry and agriculture. For the 2.8 million km of overall river length in mainland China, about 34% has water quality graded as worse than Grade IV (see Figure 7). Regarding the groundwater quality, of the assessment area of 1.97 million km^2, about 63% of the water quality is grade IV or V (Wang 2010).

5.13.3.6 Groundwater Overdrafting

Around half of all of China's wheat is produced in North China, where the water shortage is severe; consequently, groundwater is pumped out to irrigate the croplands. Therefore, groundwater overdrafting is a very common issue in North China, and in some regions it becomes a very serious problem. For example, the groundwater exploitation in Hebei province was 13 billion m^3 year^{-1} in the 1980s, with groundwater table depths of 170–350 m. In the 1990s, the amount was 16 billion m^3 year^{-1}, with water table depths of

Table 5 Growth rates (%) of water use for the industry and urban domestic sectors in China since 1980 (Wang 2010)

Sector	*1980–85*	*1985–90*	*1990–95*	*1995–2000*	*2000–06*	*1980–2006*
Industry	4.7	5.7	7.3	3.4	1.8	4.4
Urban domestic	8.5	7.2	6.3	6.9	4.9	6.7

Grade	Length(km)
I	19 717
II	106 781
III	61 765
IV	33 304
V	17 925
Worse than V	45 552

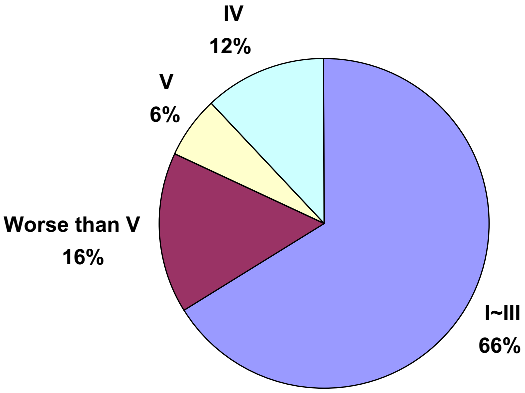

Figure 7 Surface water quality in mainland China in 2006. Adapted from Wang, H., 2010: *Water Resources Challenges and Policies in China*. Public Lecture, Hong Kong.

250–380 m (Shao and Hu 2002). Another consequence of groundwater overdrafting is loss of wetlands. It is reported that 90% of the wetlands in Hebe province have disappeared since 1960, and streams and creeks have been dried up. The largest natural freshwater lake in the Hai River basin, Baiyandian Lake, is losing area and becoming grossly polluted (Griffiths 2006). Regarding urban areas, groundwater overdrafting in the cities of Shanghai (Wei 2006), Beijing (Zhang and Kennedy 2006) and Tianjin (Bai and Imura 2001), for example, resulted in declines of the water tables and groundwater storage. Land subsidence (Yin et al. 2006; Zhang et al. 2008) has occurred in urban areas in association with groundwater overdrafting.

5.13.4 Possible Influences of Climate on Water Resources

A temperature increase in China over the past five decades (Piao et al. 2010) has been observed. There are serious potential vulnerabilities to China's agricultural production due to climate variations; however, no definitive conclusion can be drawn due to the uncertainties involved in climate change projection. It is possible that China's average temperature will increase further by 1–5 °C by 2100 (Meehl et al. 2007), whilst summers are likely to be much warmer (Piao et al. 2010).

5.13.4.1 Observed Climate Variations

Over the Yangtze River basin, the western, eastern, and northern parts show more well-developed increasing trends for the temperature than the southern region for the past 100 years (before 2007) (National Development and Reform Commission of China 2007). There is a seasonality to warming, with the most pronounced temperature increase occurring in winter, especially for the period of 1986–2005 (National Development and Reform Commission of China 2007), with warming in winter (0.04 °C per year) being about four times the rate of warming in summer (0.01 °C per year). Meanwhile, the warming in northern China is faster than that in southern China.

There is no obvious trend on the annual precipitation in the past 100 years in mainland China (National Development and Reform Commission of China 2007). However, since the 1950s, the annual precipitation has gradually decreased, with an average rate of 2.9 mm per decade, while regional variation is noticeable. The most obvious decease of precipitation occurred mostly in northern China and also in the eastern parts of northwestern and northeastern China, with an average rate of 20–40 mm per decade. Meanwhile, the precipitation significantly increased in southern China and southwestern China, with an average rate of 20–60 mm per decade.

The urbanization-induced temporal warming at the two stations of Beijing and Wuhan cities was analyzed (Ren et al. 2007). The study concluded that the annual urban warming accounted for 61.3 and 39.5% of overall warming in the respective cities for the period of 1981–2000. Zhou et al. estimated that the warming of mean surface temperature of 0.05 °C per decade is attributed to urbanization in Southeast China for the period of 1979–98 (Zhou et al. 2004). The local urbanization effects on weather variables in South China have also been studied (Chen et al. 2011). It was found that for the period of 1960–2005 the variations of weather variables before and after 1984 are different. Before 1984, there were no significant urbanization effects, and the daily minimum temperature ($T_{\min}$), relative humidity (RH), and precipitation (P) steadily increased but the daily maximum temperature ($T_{\max}$) decreased, resulting in a considerable decrease in the diurnal temperature range (DTR) and a slight decrease in the surface temperature. After 1984, $T_{\min}$ and $T_{\max}$ increased considerably, and an urbanization influence on $T_{\min}$, but not $T_{\max}$, is observable. The urbanization effect causes an additional increasing trend in $T_{\min}$ with a rate of about 0.6 °C/decade, and also results in a decreasing trend in both DTR and RH in the urban area. The urbanization influence results in a near-uniform increase of $T_{\min}$ for all four seasons and a strong decrease of RH in summer and autumn. Moreover, there is no significant change in precipitation at the annual scale, but an increasing rate of 11.8% per decade in summer was detected (Chen et al. 2011). With the urbanization influence, a considerable increase in precipitation is noticeable at the annual scale; specifically, the increasing rates of 18.6% per decade in summer and 13.5% per decade in autumn are observed.

5.13.4.2 Temporal Change of Water Resources

The Ministry of Water Resources in mainland China assessed the situation for water resources over two periods, 1956–79

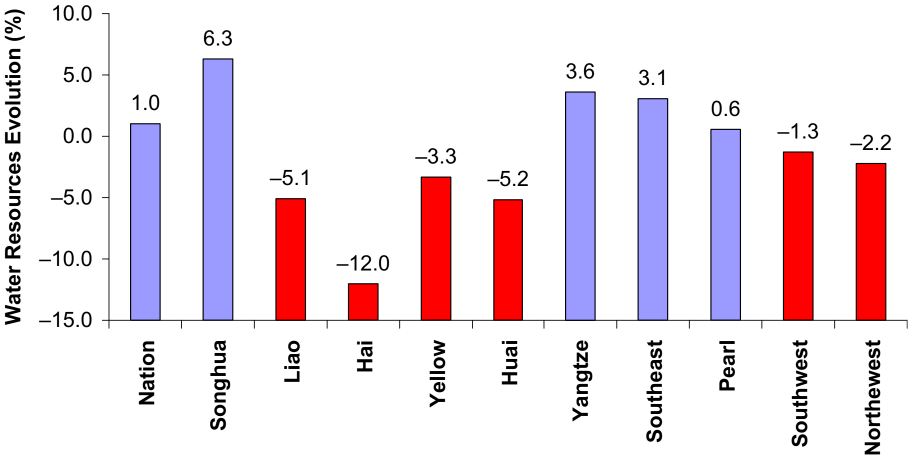

Figure 8 Water resource evolution between 1956–79 and 1980–2000 in mainland China and different river basins. Adapted from Wang, H., 2010: *Water Resources Challenges and Policies in China*. Public Lecture, Hong Kong.

and 1980–2000. It was found that the precipitation was 10% less, 6.9% less, and 2.6% less in the second period compared with the first period in the Hai River basin, the Yellow River basin, and the Liao River basin, respectively. In contrast, the precipitation was 3, 4.6, 2.6, and 6.5% more in the second period in the Yangtze River, the Songhua River, and the two river basins in southeastern and northwestern China, respectively. Except for the Songhua River basin and the rivers in southwestern China, the annual average potential evaporation was 5.4% less in the second period than in the first period. Shen (2010) indicated that the main reasons for the potential evaporation decrease between the two periods were the change of sunshine percentage, wind speed, and increase in air humidity during the second period.

From the assessment of the Ministry of Water Resources, the surface water resources and total water resources in mainland China have increased slightly in the second period, corresponding to the slight increase in precipitation. However, there are spatial differences as reflected by the various river basins, and Figure 8 shows the change in water resources for the two periods 1956–79 and 1980–2000. In the second period, total water resources in southern China increased by 5%; however, the water resources in northern China have clearly decreased, especially for the Yellow River basin, the Hai River basin, and the Liao River basin (Shen 2010). In the Hai River basin, there was a 10% decrease in precipitation, 41% decrease in runoff, and 25% decrease in total water resources. In the Shandong Peninsula of the Huai River basin, there was a 16% decrease in precipitation, 51% decrease in runoff, and 34% decrease in total water resources. Shen indicated that the reason for the water resource decrease in north China is the reduction in precipitation and landscape change (Shen 2010). Comparing the current land covers with those of 50 years ago, 35% of the areas in the Yellow River, Huai River, Hai River, and Liao River basins have been changed; generally, the runoff is decreased by 10–20% in normal precipitation years and by 15–40% in dry years (Shen 2010).

Over mainland China, the analysis of the past weather data revealed that heavy rainfall events happened more frequently over northwestern China and in the middle and downstream areas of the Yangtze River, but not in northeastern China (Zhai et al. 2005). There is a general decrease in terms of rainy days across the country (Piao et al. 2010). The Yellow River is sensitive to drying trends. A persistent decrease in runoff is observed. This is attributed to both climate impacts and overextraction of water for irrigation, industry, and domestic usages. There has been a small increase (not statistically significant) in annual runoff for the Yangtze River since 1960 (Piao et al. 2010). A decrease in runoff has occurred in many gauged headwater catchments in the autumn, whilst a positive runoff trend is observed for the midstream and downstream sections of the Yangtze River, owing to the increasing precipitation in this region. Northwestern China, especially the arid area, has experienced a decline in the occurrence of severe drought, which is evidenced by both rising lake levels and increasing vegetation cover in areas adjacent to deserts (Piao et al. 2010).

5.13.4.3 Glacier Melting

China has 46 377 glaciers, with a total area of 59 425 km^2 (Li et al. 2008). The glaciers shrank by 7%, which is equal to 3790 km^2, in the Qinghai-Tibetan Plateau in the past four decades (Li et al. 2008). The runoff owing to the glacier melting has increased from 62 km^3 in 1980 to 66–68 km^3 in 2000 (Li et al. 2008). Piao et al. (2010) presented a case study of glacier retreat and melting influence in the Tarim River basin in Northwest China, showing that the melting of glacier has increased the local runoff by 15% between 1957 and 2000; however, due to rapid development of oases in the basin, the increased runoff can not satisfy the water demand (Hao et al. 2008), and the runoff in the Tarim river mainstem has decreased. Gurung et al. (2011) indicated that changes in snow cover for the western Himalaya are primarily due to interannual variations in circulation patterns as there is the correlation between the amount of annual snowfall and annual seasonal snow cover.

Warming in spring and early summer would increase runoff due to glacier melting (Barnett et al. 2005; Liu et al. 2009). Nevertheless, the vulnerability of the glaciers to the warming in

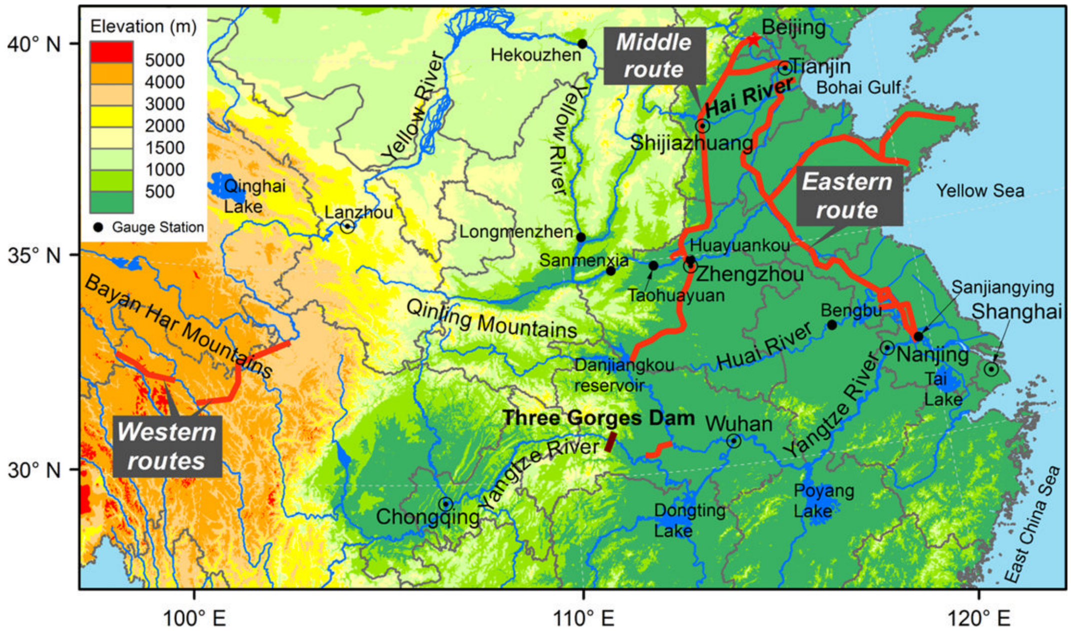
Elevation (m)
5000
4000
3000
2000
1500
1000
500
● Gauge Station
40° N
35° N
30° N
100° E
110° E
120° E
Middle route
Eastern route
Western routes
Beijing
Tianjin
Bohai Gulf
Hai River
Shijiazhuang
Hekouzhen
Yellow River
Yellow River
Qinghai Lake
Lanzhou
Longmenzhen
Sanmenxia
Taohuayuan
Huayuankou
Zhengzhou
Yellow Sea
Sanjiangying
Shanghai
Bengbu
Nanjing
Tai Lake
Bayan Har Mountains
Qinling Mountains
Danjiangkou reservoir
Huai River
Three Gorges Dam
Wuhan
Yangtze River
Yangtze River
Yangtze River
Chongqing
Dongting Lake
Poyang Lake
East China Sea

Figure 9 Three routes of South-to-North Water Diversion Project and four river basins (the Yangtze River, Yellow River, Hai River, and Huai River).

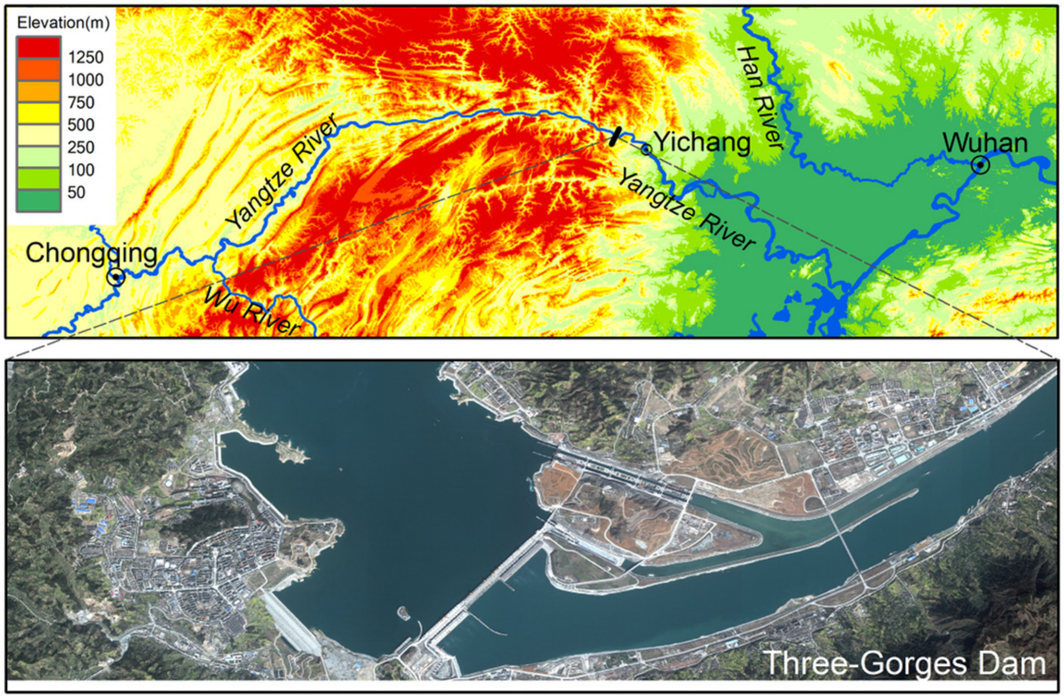
Elevation(m)
1250
1000
750
500
250
100
50
Han River
Yichang
Wuhan
Yangtze River
Yangtze River
Chongqing
Wu River
Three-Gorges Dam

Figure 10 Location of the Three Gorges Dam.

mainland China is still uncertain. Generally, about 5–27 and 10–67% of glacial areas are projected by some researchers to melt by 2050 and 2100, respectively (Shi and Liu 2000; Xie et al. 2006); they project that glacier melt peak would occur during the period of 2030–2050 (Xie et al. 2006; Chen et al. 2005). According to the China Meteorological Bureau, all small glaciers less than 2 km^2 would disappear if the temperature increased by 1.9–2.3 °C in northwest China.

5.13.4.4 Future Water Resources

Future projections of climate claim a large range of uncertainty on the question of whether northeastern China will continue to confront droughts in the future (Piao et al. 2010). A decrease of drought in northwestern China is projected under the Intergovernmental Panel on Climate Change (IPCC) B1 scenario (Nakićenović and Swart 2000), while the bipolarity of a drier

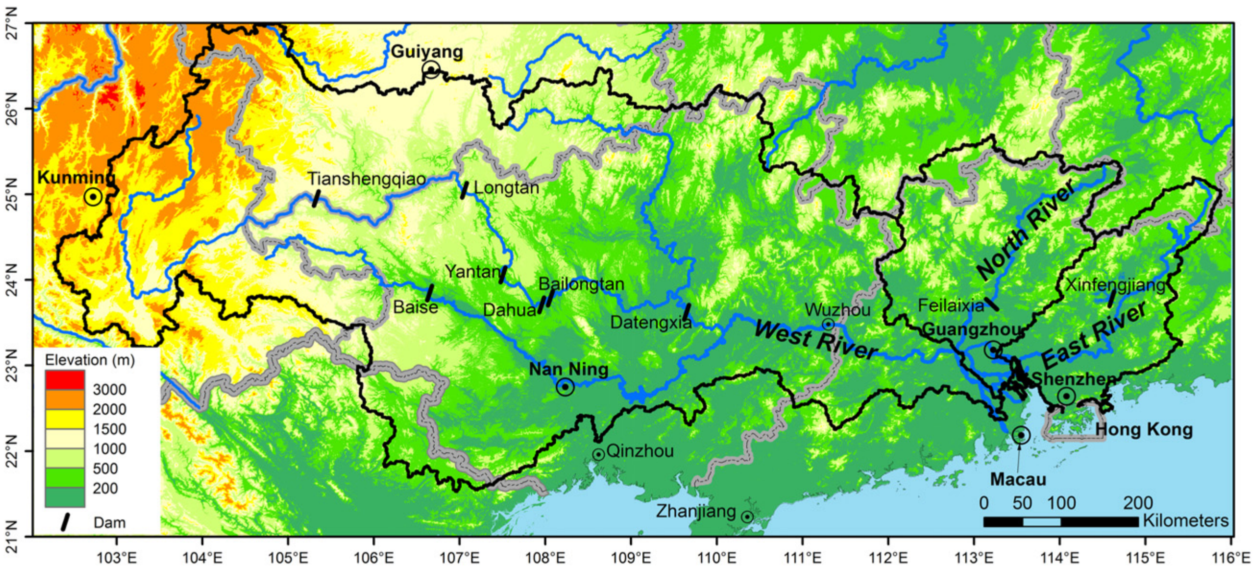

Figure 11 Pearl River basin and major dams.

northeast China and a wetter northwest China would further increase under the IPCC A1B scenario (Nakićenović and Swart 2000).

The future river runoffs and water resources in mainland China have also been studied by using projected precipitation changes (Piao et al. 2010; Meehl et al. 2007; Shen 2010). Due to the large uncertainties involved in projected precipitation, no firm conclusions can be given (Meehl et al. 2007). However, it has been suggested that in general, by the end of 2100, the river runoff would be increased over mainland China (Zhang et al. 2007a) by 7.5% under the IPCC B1 scenario, and by 9.7% under the A1 scenario (Nakićenović and Swart 2000). Annual runoff in the Yellow River basin is projected to increase by 11% (Zhang et al. 2007b) in IPCC A2 scenario (Nakićenović and Swart 2000) and by 5% in the IPCC B2 scenario (Nakićenović and Swart 2000). However, these results are dependent on the accuracy of global climate projections, and Gao et al. (2008) suggested that an accurate high-resolution climate model for mainland China is one of the necessary requirements for skillful future climate projections.

5.13.5 Tackling the Water Resource Problems

In the following subsections, three examples are introduced—the South-to-North Water Diversion project, the Three Georges project, and the practices for managing the Pearl River water resources—to illustrate some measures that have been implemented in order to deal with water resource problems in mainland China.

5.13.5.1 South-to-North Water Diversion Project

The spatial distribution of China's water resources is extremely uneven. The sum of water resources in the Yellow River and the Hai River is less than 6% of the nation's total water resources, but they need to supply water for approximately 40% of the total irrigation land. Moreover, since the late 1970s, northern China has experienced rapid urbanization and economic development; to meet urban and industrial demands for water, groundwater in the region has been overexploited. Land subsidence and regional sandstorms have caused serious environmental problems due to the excessive usage of water resources, and the water shortage is extremely serious in northern China. The Yangtze River generates more than 80% of the nation's total runoff, but its irrigation land area is approximately 30% of the nation's total. To resolve the uneven spatial distribution of water resources, the largest water diversion project in mainland China, namely the South-to-North Water Diversion Project (see Figure 9), has been planned and implemented.

The project is expected to be completed by 2050, and eventually 44.8 billion m^3 of water will be diverted to the north region from the Yangtze River basin annually. This large water diversion project will integrate the water resources in the four river basins, which are the Yangtze River, the Yellow River, the Huai River, and the Hai River. The project consists of three water transferring routes—the Eastern, Middle, and Western Routes—which divert 14.8 billion $m^3 year^{-1}$, 13.0 billion $m^3 year^{-1}$, and 17.0 billion $m^3 year^{-1}$ of water to the north, respectively. These three routes are briefly described in the following sections.

5.13.5.1.1 Eastern Route

Construction of the Eastern Route started in December 2002, and the route is expected to be completed by 2030. The Eastern Route is 1155 km long and diverts water from the downstream Yangtze River via the ancient Beijing-Hangzhou Grand Canal. It is the longest canal in the world and the oldest parts were constructed in the fifth century BCE (Before the Common Era). The main purpose of the canal was to transport grain and other commodities to the Huang River, Huai River, and Hai River plains (in Jiangsu, Anhui, and Shandong provinces), to Tianjin, and finally to Beijing. This route has 23 pumping stations, 9 km of tunnels, and 634 m of siphon sections (Water Technology

2011). A total of 7.67 billion m^3 year^{-1} of water will be used to irrigate croplands, and 6.66 billion m^3 year^{-1} of water will be used to supply the domestic and industrial sectors.

5.13.5.1.2 Middle Route

The Middle Route is 1267 km long, and its construction started in December 2003. This route is expected to be fully completed by 2030. In this route, water is diverted from the Danjiangkou reservoir on the Han River, which is a tributary of the Yangtze River, via canals near the west edge of the Huang, Huai, and Hai plains to Beijing and Tianjin municipalities through Henan and Hebei provinces. The route is regarded as an optimal solution to mitigate the water resource shortage in northern China. The advantages of the route lie mainly in the good water quality and gravitational force used to drive water from the south to north. The diverted water will benefit the people living in an area of 0.16 million km^2, which is mainly composed of the Tangbaihe plain and the middle-western Huang-Huai-Hai plains, and 17 large- and medium-size cities, including Beijing, Tianjin, Shijiazhuang, and Zhengzhou.

5.13.5.1.3 Western Route

The Western Route plans to divert water from the upstream reaches of the Yangtze River to the upper reaches of the Yellow River by a 100-km tunnel through the Bayan Har Mountains. The water diverted by the route will benefit about 0.2 million km^2 of irrigated farmlands and the route will provide 9.0 billion m^3 year^{-1} of water for the domestic and industrial sectors. The main advantages of the route are that it can promote the economic development of some relatively less developed regions in northwest China and improve the environment of the Loess Plateau in North China. Nevertheless, due to the difficulties of constructing such a long tunnel and the ongoing dispute about water resources for the upstream areas of both the Yangtze River and Yellow River, the route is still in the planning stages (Sohu 2011).

5.13.5.2 Three Gorges Project (TGP)

The major task of this project is to construct the Three Gorges Dam (TGD). TGD is located in the Yiling District of Yichang City, in Hubei province, and is the largest water project along the Yangtze River (see Figure 10). Construction of TGD started on 14 December 1994, and the dam was completed on 20 May 2006. Mainly, there are four goals to the project. They are to reduce the flood risks in the midstream Yangtze River, to supply water to the midstream and downstream areas of the river, to produce clean energy, and to improve the Yangtze River's navigation condition from Wuhan to Chongqing (see Figure 10).

According to the design, all of the 26 turbines (with 700 MW generating capacity each) were installed and operating by 2009. There are six extra underground turbines, each with 700 MW generating capacity; three of these turbines were installed and functioning by 2011, with the remaining ones to be completed by 2012. With two other turbines of 50 MW as backup power units, the hydropower station of TGD dam has a capacity of 22 500 MW, which is currently the world's largest hydropower station to produce clean energy.

Flooding is a major problem for the midstream and downstream areas of the Yangtze River, where there are agricultural production bases, millions of people, and important cities such as Wuhan, Nanjing, and Shanghai. TGD can effectively control or minimize floods by using the flood storage capacity of 22 km^3 of the Three Gorges Reservoir (TGR). On 20 July 2010, there was a peak flow of 70 000 m^3 s^{-1} into the TGR, and the reservoir water level rose about 3 m within 24 h; after the TGD regulation, the reservoir outflow was reduced to 40 000 m^3 s^{-1}, which would not cause flooding downstream the reservoir. The benefit from flood control of the TGR in 2010 was estimated at more than 20 billion RMB Yuan (about US$ 2.93 billion in 2010 equivalent).

The reservoir's operational water level during the dry season is 175 m (above the sea level). On 26 October 2010, this water level was reached for the first time after TGR tried to impound water for reaching 175 m in 2008 and 2009. Accordingly, its target of 84.7 TW hour (TWh) of annual power generation was achieved in 2010. By 16 August 2011, the hydropower plant of TGP had generated 500 TWh of electricity since the first operation of a hydropower generator in 2003. In addition, with the improvement of the navigation condition of the Yangtze River reach from Yichang to Chongqing due to the TGR, the maximum freight capacity of a ship has increased from 3000 tons before the project to 10 000 tons after the project. On 25 December 2011, a historical high was achieved in which an annual total of 100 million tons of cargo was transported through the TGD ship locks.

Nevertheless, there are some negative impacts associated with TGP. For example, some archaeological and cultural sites have been submerged by TGR, and 1.3 million people have been relocated. The river ecosystem would have been influenced by regulating natural flow, and the rising and falling of water levels in the range of 145 and 175 m annually has resulted in some geological natural hazards (e.g., landslides). The impoundment of the TGR may impact the downstream lake levels and associated ecosystems, particularly Dongting and Poyang Lakes (Fan 2011). The scouring of riverbeds by water released from TGR is also a negative effect. Moreover, it has been argued that a massive reservoir like TGR might affect the climate systems and trigger more extreme weather and climate events (Wu et al. 2006; Gleick 2008). However, research has confirmed that TGR may influence the weather of the regions only to approximately 10 km away from the reservoir (Zhang et al. 2004).

5.13.5.3 Water Resource Management in the Pearl River

Figure 11 shows the geographic location of the Pearl River basin. Along with the rapid socioeconomic development of the Pearl River delta since the late 1970s, the water demand from the region has dramatically increased and various water problems (e.g., water shortages during droughts, water pollution, and seawater intrusion) have appeared (Cui et al. 2007; Niu and Chen 2010; Wang 2010). To deal with these problems and other issues in the basin, the Pearl River Water Resources Commission (PRWRC) has implemented a series of measures.

5.13.5.3.1 Water Allocation Framework

The water allocation framework established by the PRWRC aims to protect the upstream water sources, to regulate the midstream development, and to harness the downstream environment (Cui et al. 2007; Wang 2010). The aims of water protection in the upstream are to maintain the water quality, to prevent soil erosion, to recover the polluted lakes, to protect ecological systems, and to enhance the construction of small- to middle-scale water conservancy projects. Water regulation in the midstream area is achieved by the construction of a series of water regulation projects and by increasing the capability of allocating water for maintaining navigation and achieving an ecology-required minimum flow during extreme dry periods. For example, through the National Headquarters on Flood Control and Drought Relief, the PRWRC implemented the release of water from a series of the reservoirs, most of them located in the midstream area, for preventing seawater intrusion in the estuarine areas in early 2005 (Cui et al. 2007). Water harnessing in the downstream area aims to enhance the prevention and treatment of the water pollution, to build a water-saving and pollution-preventing society, to handle the outlet salinity problem, and to conduct optimization projects for the water resource allocation.

5.13.5.3.2 Key Water Projects

The existing key water projects in the Pearl River basin include the Feilaixia, Bailongtan, Baise, Dahua, Yantan, Longtan reservoirs and the Tianshengqiao hydro projects (see Figure 11). A project currently being planned is the Datengxia Dam, which will be a key regulation project to safeguard water supply for Macau city and the Pearl River delta. Regional water diversion projects include the Zhanjiang and Qinzhou projects, and the Xijiang and Hongling projects along with a scheme to divert water to the middle of Guizhou province.

Key water-saving projects currently being undertaken include the Mengkaige Irrigation Area and the Youjiang Irrigation Area water-saving projects. Irrigation and drinking water projects are mainly constructed in Yunnan and Guizhou provinces for agricultural irrigation and water supply, and they include the Rundian and Ziqian projects. A special campaign called the Projects with Five Smalls has been launched; these projects include construction of small water pools, small vaults, small dykes, small channels, and small pumps for the effective storing and transferring of water.

5.13.5.3.3 Future Water Demand

By 2030, the projected total water demand over the Pearl River basin in a normal year is 93.9 billion m^3 $year^{-1}$, which is 6 billion more than current demand (Wang 2010). The projected agricultural supply is 56% (53 billion m^3), industry demand is 30% (27.7 billion m^3), and domestic water is 14% (13.2 billion m^3), while the basic flow for in-stream use is 130.3 billion m^3. Urban water use is 37.6 billion m^3, which is 15.8 billion m^3 more than the current demand and approximately 40% of the total protected water use in 2030.

5.13.6 Concluding Remarks

Population growth is the dominant factor of threatening the security of water resources. Since 1979, the one-child policy has been implemented in mainland China. It was estimated that by 2007 China prevented about 400 million births (Anonymous 2011). The efforts to control population growth have undoubtedly mitigated the severity of water shortage. However, the various water resource problems mentioned above are still serious, especially given the prediction of a projected population peak of 1.5 billion around 2033.

The strategies and measures for tackling the vulnerability of water resources in mainland China (Wang 2010) include changing from supply-oriented water management to demand-oriented management and establishing a water-saving society by adjusting the economic structure and industrial layout. The water resource management authorities are carrying out the strictest water management system and increasing the utilization of other water resources, such as reclaimed water and seawater desalinization. Also, the water resource commissions for the river basins are improving the water regulation, promoting rational water allocation, building necessary water infrastructures, strengthening their water regulation capabilities, promoting the use of information-based technology applications, and strengthening integrated water management.

The current situation of water resources and their management in mainland China are not able to meet the increase in demand of water-related usages, such as water supply, protection of the water environment, and prevention of water-related natural hazards, due to population growth, the need to produce food, and the rapid economic development since the late 1970s. Regarding this, Central Document No. 1 in 2011 (Central Committee and State Council 2011), entitled "The Decision on Accelerating the Reform and Development of Water Conservancy," was issued on 29 January 2011. This document is the first comprehensive policy document on integrated water resource management released by the Central Committee and State Council of mainland China. Water resource management, as the first priority among national infrastructure construction, will be pushed forward by both the central government and local governments.

The main tasks identified in Central Document No. 1 include five parts (Central Committee and State Council 2011). Firstly, the water conservancy construction in rural regions and other vulnerable water-related natural hazard areas will be strengthened. Secondly, the harnessing of large rivers and lakes, water resource allocation, and water and soil conservation will be accelerated in a sound manner. Thirdly, significant financial allocation to water projects will be made. Funds for water resources management projects will be raised from multiple channels, and it is expected that a total of 4 trillion RMB Yuan (about US$ 0.6 trillion in 2011 equivalent) will be invested into the water projects for the next 10 years (i.e., up to 2020). Fourthly, the strict management of water resource usage will be enforced, which sets restriction standards for the control of water resource development and utilization, the control of water use efficiency, and the pollution load in water use zones. Fifthly, innovation of the water management system and mechanism will be continuously carried out. It is expected that by 2020 a comprehensive flood control and drought mitigation system in mainland China will be established and urban flood prevention and flood control capacity will have been greatly improved. The total water use for the whole country by 2020 will be limited to 670 billion m^3 $year^{-1}$, and the effective utilization coefficient of irrigation water will reach 0.55.

The possibility of the frequent and sudden occurrence of extreme weather events could increase due to climate change, and new water-related problems are raised in conjunction with the growth of population and the fast development of China's economy. Despite the many challenges in water resource management, including the frequent floods, droughts, and deterioration of the water environment, China has made great efforts in flood control, drought relief, and environmental protection in recent years. Both structural and nonstructural measures have been implemented, which include establishing an institutional framework, improving structural facilities, developing emergency plans, strengthening flood forecasting and warnings, issuing laws and regulations, and enhancing emergency management.

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5.14 Recent and Historic Andean Snowpack and Streamflow Variations and Vulnerability to Water Shortages in Central-Western Argentina

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5.14.1 Introduction

In many mountainous regions of the world the accumulation of snow during winter constitutes the main (and sometimes the only) source of streamflow during subsequent warmer months and throughout the year. The dramatic changes in topography within short distances in mountain ranges usually force air masses to release their moisture as they ascend and move across the highest peaks and intermontane valleys. With freezing temperatures, this precipitation usually occurs as snow, and this water can accumulate and remain frozen until warmer conditions start the seasonal, gradual melting of the snowpack that feeds many creeks and rivers in high-elevation regions. This capacity of mountainous areas to accumulate and store water as snow and ice during winter and subsequently release it as meltwater during warmer months, when it is most needed by human populations in adjacent areas, has been recognized and valued by ancient and modern societies in many parts of the world. In recent decades, the importance of mountains as storage and sources of water has been reaffirmed through numerous studies, and the expression 'water towers of the world' has been coined to reflect the crucial significance of these elevated regions to the population and environments in different continents (Viviroli et al. 2009, 2011). However, despite the well-known and generally undisputed importance of mountains as primary sources of freshwater, the number of detailed assessments of the main hydrologic patterns and the factors affecting mountain climate conditions remains limited in many regions. In such cases, the vulnerability of local human populations to water shortages has not been assessed through a comprehensive hydroclimatologic and socioeconomic approach that could help identify, for example, those social and economic sectors more vulnerable to extended droughts, or minimum water levels required for 'normal' operation of local societies.

This chapter provides an overview of recent empirical analyses of snowpack and streamflow records from the Andes between 30 and 37° S (Figure 1), which allow an assessment of the importance of the winter snow on regional river discharges and the identification of their main temporal and spatial patterns over the past 100 years. The relationships between mountain snowpack records and various large-scale ocean–atmospheric variables (such as sea-surface temperatures and the El Niño–Southern Oscillation, ENSO) are also assessed in an attempt to identify the main factors modulating snowpack variations in the Andes. Two complementaries, recently developed Andean snowpack reconstructions covering the past two to eight centuries, are subsequently examined and their main intra- to multidecadal (IMD) patterns identified using time series analysis techniques. Besides the more obvious application in local water management and regional development strategies, this information allows testing the relative significance of the patterns of snowpack observed during the instrumental period in a long-term context. This information may also be relevant for measuring the strength and time stability of the relationships between Andean snowpack and ENSO or other ocean–atmosphere features over most of the past millennium. Finally, the authors comment on the varying vulnerabilities to water shortages in the basin of Río Mendoza (one of the main rivers in central-western Argentina, Figure 1) and the potential benefits of integrating instrumental and reconstructed hydrologic data together with results from climate and climate-driven hydrological models into local socioeconomic assessments, water management practices, and adaptation planning.

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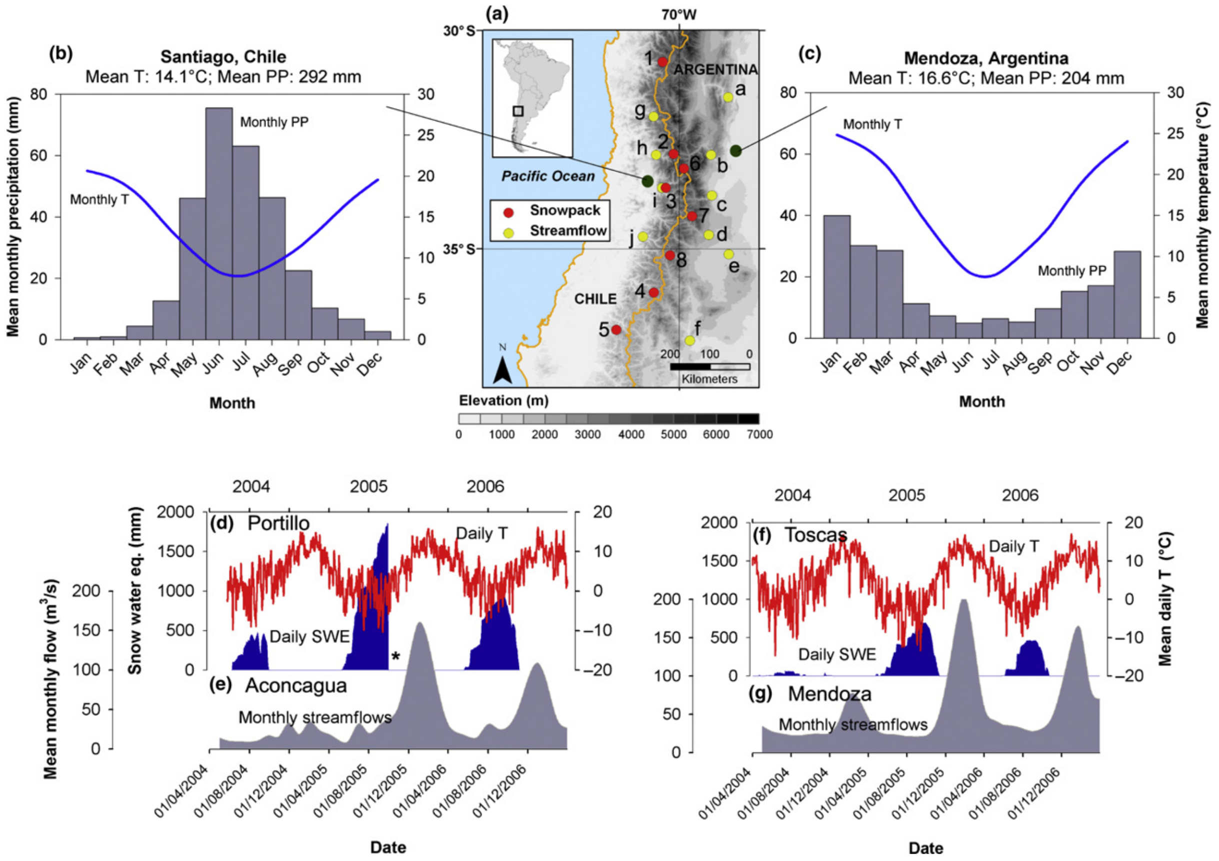

Figure 1 (a) Location of the stations with the longest and most complete snowpack and streamflow records (red and yellow dots, respectively) in the Andes of Chile and Argentina between 30 and 37° S. For station metadata see **Table 1**. (b, c) Climographs showing the climatic regimes characteristic of the cities of Santiago, Chile, and Mendoza, Argentina, on the western and eastern lowlands adjacent to the Andes. To facilitate the comparison of these diagrams, mean monthly precipitation (left *y*-axes) and temperature (right *y*-axes) are depicted using the same scale. The units for the precipitation axes are indicated in (b) and the temperature axes are labeled on the far right in (c). Note the different climatic regimes between these sites with a marked peak in precipitation during the austral winter (summer) for Santiago (Mendoza). (d) Mean daily temperatures (red line) and snow water equivalent (blue area) recorded at Portillo, Chile (station 2 in (a)) between 1 April 2004 and 31 March 2007. These years were selected because they provide a good indication of the range of conditions existing in the high arid Andes: the winter of 2004 was extremely dry, that of 2005 was extremely snowy, and that of 2006 was slightly above 'normal.' An asterisk (*) indicates partial lack of data for the 2005 snow season. (e) Mean monthly discharges for Río Aconcagua at Chacabuquito (station h in (a), located downstream of Portillo) between April 2004 and March 2007. Note the good correspondence between the amount of snow accumulated in the basin headquarters during winter and the streamflow recorded during the following warmer months. (f) Same as (d) but for the Argentinean station Toscas, on the eastern side of the Andes (station 6 in (a)). (g) Same as (e) but for Río Mendoza at Guido, downstream from Toscas (station b in (a)). The left axes in (d)–(g) are labeled on the far left and the right axes are labeled on the far right, and the data for Portillo–Aconcagua are depicted in the same scale as those for Toscas–Mendoza to facilitate the analysis of similarities and differences on both sides of the Andes.

5.14.2 Andean Snowpack Is a Crucial Water Resource in Vast Semiarid Areas of Southern South America

The portion of the Andes between 30 and 37° S in southern South America (Figure 1(a)) has a mean elevation of about 3500 m, with several peaks reaching over 6000 m. The weakening and northward displacement of the subtropical Pacific anticyclone during the austral winter enhances the westerly flow across central Chile, producing a marked cold season peak of precipitation in the lowlands and over the mountains to the east (Miller 1976; Aceituno 1988; Falvey and Garreaud 2007; Figure 1(b)). Owing to the high elevation and north–south orientation of the cordillera, most of the moisture from the Pacific air masses is released in the mountains and little Pacific moisture reaches the easternmost slopes of the Andes in Argentina. The semiarid region east of the cordillera experiences a continental regime with a marked warm season precipitation peak associated with moist air masses from the northeast as well as convective processes (Prohaska 1976; Figure 1(c)).

Several heavily populated cities (including Santiago de Chile, the nation's capital city, and the city of Mendoza, in central-western Argentina) and extensive agricultural areas are located in the lowlands flanking the Andes at these latitudes. Human activities in these productive regions are almost entirely dependent on the systematic use of mountain meltwater for human consumption, industries, irrigation, hydroelectric generation, and aquifer recharge. Collectively, over 10 million people live in these regions (INDEC 2001; INE 2003) and enjoy the socioeconomic, recreational, and environmental benefits provided by this natural resource. The dependence on Andean freshwater is even more evident along the eastern, drier Argentinean foothills and plains, which receive on average only 200 mm of precipitation per year (**Figure 1(c)**). The development of complex irrigation systems has allowed the existence of oases that stand out as islands of green amid vast oceans of dry lands, forming a territorial pattern common to human settlements across central-western Argentina. For example, in the Province of Mendoza oases represent only 3% of the total surface but contain about 98% of the population and concentrate a large share of the more dynamic socioeconomic activities. Given these particular environmental and socioeconomic conditions, water scarcity is not just a hydroclimatic phenomenon in this region. These Latin American drylands have been characterized as 'hydraulic societies' (Worster 1985), as social tissues are strongly associated with intensive use of water resources that historically have been adapted to 'control' a hostile natural environment. While the space becomes territory through water allocation, water appropriation and use gives rise to and reproduces a scheme of social and political relationships in which quotas of power are distributed. Although water deficits are structural, water shortage scenarios threaten local economies and anticipate increases in the frequency and intensity of social, political, and economical conflicts (Montaña 2008). In this context, efforts to bridge knowledge derived from natural and social sciences may provide very interesting perspectives, as better knowledge of the relative magnitude and temporal extension of past droughts (and their potential behavior in the future) constitutes a valuable resource to anticipate future vulnerabilities and develop adaptation strategies toward resilience.

As in many regions with snowmelt-dominated hydrologic regimes, in the Andes of central Chile and central-western Argentina there is a well-known, strong, direct relationship between winter snow accumulation and spring–summer river discharges (see, e.g., **Figure 1(d)–1(g)**). Local water agencies in Chile and Argentina are well aware of this relationship and have implemented a network of measuring stations that regularly monitor the accumulation of snow during the winter at several high-elevation sites. The snowpack information (which for some sites spans over five decades of continuous records) is routinely used to produce warm season and annual water supply forecasts for the main river basins on both sides of the Andes. Interestingly, however, besides these short-term forecasting products, very few analyses of instrumental snowpack variations are available for this portion of the Andes, and the main spatiotemporal patterns in these mountain snow records are only starting to be understood.

Major rivers in this region have also been monitored for several decades using a relatively small but well-maintained network of gauging stations. Some of the mean monthly streamflow records available for these rivers cover almost the entire twentieth century and are of excellent quality. This is a rarity for Andean South America, which generally lacks long, good-quality hydroclimatic data. There are also records from other smaller rivers and creeks that generally span for a few decades but in some cases contain periods with missing information. However, despite the existence of these valuable records and the well-known, crucial socioeconomic importance of mountain meltwater, the number of studies assessing the main patterns of IMD variations in river discharges is limited (see later).

5.14.3 Andean Snowpack and Streamflow Records Share a Strong Regional Common Signal

Masiokas et al. (2006) presented the first attempt to integrate snowpack records from Chilean and Argentinean stations and provided a comprehensive assessment of maximum winter snow accumulation data over the 1951–2005 period. Their results generally agreed with previous climatic and hydrometeorological studies showing a marked Pacific, ENSO-related influence on precipitation in this area (e.g., Rutlland and Fuenzalida 1991; Compagnucci and Vargas 1998; Escobar and Aceituno 1998; Montecinos and Aceituno 2003). However, their analyses provided further insight into the main temporal and spatial patterns in the snowpack records and their relationships with local climate, ENSO events, and large-scale atmospheric variables. Masiokas et al. (2006) also quantified the relationship between winter snow records and river discharges in the region and evaluated possible causes for the observed streamflow and glacier trends over the second half of the twentieth century.

Masiokas et al. (2006) showed that, despite the very low number of snowpack records existing in the Chilean and Argentinean sides of the Andes between 30 and 37° S, these records share a high percentage of common variance at interannual and longer timescales. These analyses were based on maximum winter snow water equivalent values (MSWE) as a surrogate for total snow accumulation at each site and a regional record developed from the six stations with the longest and most complete records. This dataset has subsequently been expanded and updated (e.g., Masiokas et al. 2010, 2012; **Figure 2**), although the number of stations remains small compared to other regions such as western North America or the European Alps (**Figure 2(a) and 2(b)**; **Table 1**). Collectively, these records currently cover different portions of the 1951–2010 period, and despite the large latitudinal range of the stations the mean correlation coefficient from all possible paired combinations is 0.683. These individual snowpack records show a strong year-to-year variability ranging from 0% to over 400% of their long-term mean, and the snowiest and the driest winters are concurrently captured in most records throughout the region (**Figure 2(a)**).

Examination of streamflow records shows even stronger similarities than the snowpack records (**Figure 2(b)**; Masiokas et al. 2010). The stronger streamflow similarities probably relate to the overall lower quality or regional representativeness of the snowpack data plus the different inherent characteristics of snowpack and streamflow interannual variations in this region. However, when the individual records are aggregated into regional averages, the similarities between the MSWE and the streamflow series are remarkable, with a very strong time-stable common signal at interannual and interdecadal timescales (**Figure 2(c)**). This result is not surprising given the predominant role of snowmelt in the river discharges of this region. It is interesting to note, however, that the first

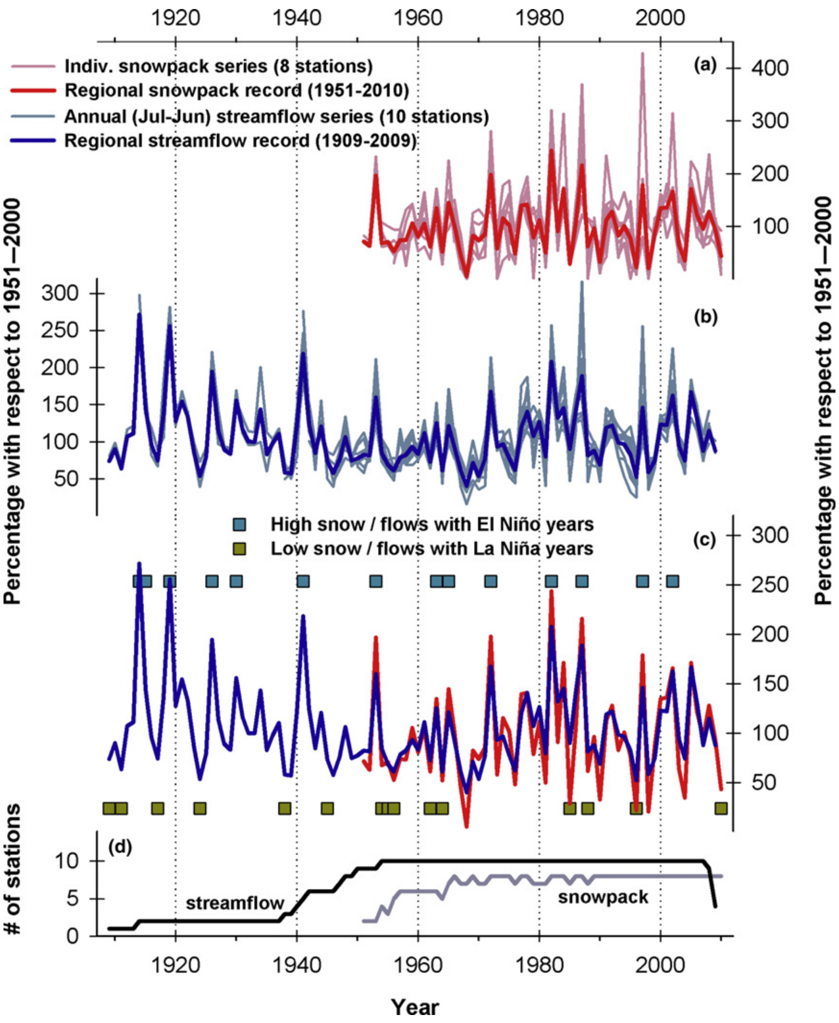

Figure 2 (a) Winter maximum snow water equivalent records (pink lines) for the eight snowpack stations shown in Figure 1(a). The 1951–2010 variance-adjusted regional snowpack average is shown with a red line. (b) Jul.–Jun. mean annual series (light blue lines) of the 10 streamflow stations in Figure 1(a), together with a regionally averaged river discharge record (blue line). (c) Comparison of the regional records of winter snowpack and mean annual streamflow (red and blue lines, respectively) shown in (a) and (b). The Nov.–Feb. river discharge record (not shown) portrays virtually identical features to the annualized data. El Niño years (Giese and Ray 2011; light blue boxes) generally coincide with above-average hydrologic measurements in the Andes. La Niña years (ochre boxes) usually reflect an opposite pattern – dry years in the Andes – but there are notable exceptions such as the extremely dry winters of 1968, 1998, and 2004, which did not coincide with La Niña events in the tropical Pacific. (d) Number of stations used to compute the regional snowpack and streamflow records in any given year. All series in (a)–(c) are expressed as percentages with respect to the 1951–2000 common period mean, but note the different scales used in each case.

integrative, quantitative analyses using data that cover the past several decades and from the eastern and western slopes were not performed until very recently (Masiokas et al. 2006, 2010).

As expected from a snowmelt-dominated regime, the late spring–early summer months (Nov.–Feb.; which account for almost 60% of the annual total flows) show the highest correlations with the snowpack record (Masiokas et al. 2006). The correlation between the MSWE record and the regionally averaged mean annual streamflows is almost high ($r = 0.922$, Figure 2(c)). These results clearly reflect the crucial influence of mountain snowpack on freshwater availability in the adjacent lowland areas in Chile and Argentina and suggest that, at a regional scale, *c.*85% of the streamflow variance observed over the past six decades could be explained by the snowpack record alone (Figure 2(c)). This also suggests that despite the low number of stations used in these analyses, the simple regional series depicted in Figure 2(c) can be considered relatively reliable indicators of the main interannual and interdecadal (IMD) hydrologic variations that occurred in this portion of the Andes approximately during the past 100 years.

As in many other mountainous areas of the world, in the Andes of central Chile and central-western Argentina the glaciers and periglacial features such as rock glaciers constitute important water resources and may contribute with significant amounts of meltwater to the surface runoff of a certain basin. The hydrological significance of the existing ice masses in this arid region becomes particularly important during extremely dry years when little or no solid precipitation occurs at the upper watersheds. Unfortunately, very few systematic, local assessments are available to properly evaluate the relative

Table 1 Snowpack and streamflow records used in this study

Variable	*Station*	*Latitude, longitude*	*Elevation (m)*	*Period*	*Average*	*Data source*
Snowpack	1–Quebrada Larga	30°43′ S, 70°22′ W	3500	1956–2010	222 mm	DGA
	2–Portillo	32°50′ S, 70°07′ W	3000	1951–2010	637 mm	DGA
	3–Laguna Negra	33°40′ S, 70°08′ W	2768	1965–2010	584 mm	DGA
	4–Lo Aguirre	36°00′ S, 70°34′ W	2000	1954–2010	943 mm	DGA
	5–Volcán Chillán	36°50′ S, 71°25′ W	2400	1966–2004	800 mm	DGA
	6–Toscas	33°10′ S, 69°53′ W	3000	1951–2010	295 mm	DGI
	7–Laguna del Diamante	34°15′ S, 69°42′ W	3310	1956–2010	453 mm	DGI
	8–Valle Hermoso	35°09′ S, 70°12′ W	2275	1952–2010	784 mm	DGI
Streamflow (river)	a–Km. 47.3 (San Juan)	31°32′ S, 68°53′ W	945	1909–2008	65.2 $m^3\ s^{-1}$	SSRH
	b–Guido (Mendoza)	32°51′ S, 69°16′ W	1550	1909–2009	48.9 $m^3\ s^{-1}$	SSRH
	c–Valle de Uco (Tunuyán)	33°47′ S, 69°15′ W	1200	1954–2009	28.6 $m^3\ s^{-1}$	SSRH
	d–La Jaula (Diamante)	34°40′ S, 69°19′ W	1500	1938–2009	30.9 $m^3\ s^{-1}$	SSRH
	e–La Angostura (Atuel)	35°06′ S, 68°52′ W	1200	1906–2009	35.2 $m^3\ s^{-1}$	SSRH
	f–Buta Ranquil (Colorado)	37°05′ S, 69°44′ W	850	1940–2009	148.3 $m^3\ s^{-1}$	SSRH
	g–Cuncumén (Choapa)	31°58′ S, 70°35′ W	955	1941–2010	9.6 $m^3\ s^{-1}$	DGA
	h–Chacabuquito (Aconcagua)	32°51′ S, 70°31′ W	1030	1913–2010	33.0 $m^3\ s^{-1}$	DGA
	i–El Manzano (Maipo)	33°36′ S, 70°23′ W	890	1946–2010	107.8 $m^3\ s^{-1}$	DGA
	j–Bajo Los Briones (Tinguiririca)	34°43′ S, 70°49′ W	518	1942–2010	50.7 $m^3\ s^{-1}$	DGA

The codes used in **Figure 1** are indicated together with the stations' names. The long-term average values at each site are expressed as millimeters of water equivalent for snowpack data and cubic meters per second for mean annual (Jul.–Jun.) streamflow records. DGA, Dirección General de Aguas, Santiago, Chile (www.dga.cl); DGI, Departamento General de Irrigación, Mendoza, Argentina (www.irrigacion.gov.ar); SSRH, Subsecretaría de Recursos Hídricos, Buenos Aires, Argentina (www.hidricos.gov.ar). See Masiokas et al. (2006, 2012) for more details. Masiokas, M. H., R. Villalba, D. A. Christie, et al., 2012: Snowpack variations since AD 1150 in the Andes of Chile and Argentina (30°–37° S) inferred from rainfall, tree-ring and documentary records. *J. Geophys. Res.*, **117**, D05112, doi: 10.1029/2011JD016748.

contribution of glaciers vs. snow in a particular site at a given year (Milana 1998; Favier et al. 2009). It should be noted, however, that the hydrological contribution from glaciers is highly variable depending on the size and the glaciated area of the basin. For small basins with a large proportion of their area covered by glaciers and ice-rich periglacial features, the contribution from these ice masses is obviously very important, but as the area of the basin becomes larger, snowmelt becomes the main factor regulating streamflow and the contribution from glaciers is usually of secondary importance. The streamflow records shown in Figure 2(b) come from sites where the proportion between glaciated vs. nonglaciated area is relatively small and snowmelt is therefore the predominant factor modulating surface runoff.

Masiokas et al. (2010) extended the analyses they performed in 2006 and focused on the main IMD variations in snowpack and streamflow records using individual station data and regionally averaged series. They found that, except for three gauging stations that showed statistically significant, positive changes, linear trends in most snowpack and streamflow records are nonsignificant over the past 60–100 years of record. However, several important IMD features were identified embedded in these linear trends. These low-frequency features were more consistent and easier to identify in the streamflow series than in the snowpack data. As discussed earlier, this is probably due to the relative shortness and overall lower quality of the snowpack records, together with the more variable nature of snow accumulation at the selected locations.

The regional streamflow average depicted in Figure 2(c) was improved and updated from Masiokas et al. (2010) but essentially shows the same IMD patterns as discussed in our earlier study. In this regional series (and to a lesser extent in the individual river data, see Masiokas et al. 2010), two significant changes in mean conditions or regime shifts mark the transition between three well-defined periods (Figure 5(a)). The period between 1909 and 1944 can be characterized by wetter than normal conditions with a noticeable peak in 1914–1922. A significant drop in regionally averaged discharge flows can be observed between 1945 and 1976. This interval contains the highest concentration of extreme low flows: 4 of the 10 driest years on record occurred between 1954 and 1971 (Figure 5(a)). Conditions shifted again to above-average levels in 1977, and the 1977–1987 period is, on a regional basis, the overall 'wettest' period on record when compared to all other moving windows of 5–20 years in length between 1909 and 2009. After the extreme wet period ending 1987, the regionally averaged values dropped gradually and have fluctuated around the long-term average until recent times (Figure 5(a)). Analyses of the relative significance of all moving time windows of 5–20 years in length (Masiokas et al. 2010; Mauget 2011) indicate that despite the occurrence of some dry years after 1987, the average conditions of the past two decades cannot be considered statistically different from the long-term mean of the regional series. As expected, results for the warm season (Nov.–Feb.) regional series were extremely similar to those obtained for the annualized record (results not shown).

Other studies that have also assessed the temporal variability of streamflow records on this portion of the Andes have mostly focused on single-station records (rather than regional averages) and have generally assessed linear trends of mean monthly, seasonal, or annual series (e.g., Carril et al. 1997; Pellicciotti et al. 2007). Their results differ depending on the period or season of analysis and between river basins, but in general there is an overall agreement with the results discussed earlier, with most stations showing nonsignificant or marginally significant linear trends and with the period between the 1940s and the mid-1970s standing out as the driest interval for most sites (e.g., Carril et al. 1997). In contrast, Pellicciotti et al. (2007) report significant decreasing trends in 1970–2004 streamflows recorded at the upper section of the Río Aconcagua basin (upstream from station h in **Figure 1**). Other more recent analyses have provided complementary results regarding spatial and temporal patterns of variability and changes in the hydrological regimes of rivers flowing from the western Andean slopes in south-central Chile. Rubio-Álvarez and McPhee (2010) used seasonal and annual streamflow records from 44 rivers between 34 and 45° S and identified two main subregions with distinctive patterns of variability located north and south of the 37.5° S parallel. Annual streamflows in the northern subregion (which overlaps with the region of interest of this chapter, see **Figure 1**) showed a significant 10-year cycle, but no conclusive linear trends were found in this series or in the seasonal averages. Previous studies (Menegazzo and Radicella 1982; Compagnucci and Araneo 2005) based on streamflow records from the eastern (Argentinean) slopes have found that at these latitudes the rivers share a large percentage of common variance and could be considered relatively homogeneous over the instrumental period.

Cortés et al. (2011) analyzed the streamflow distribution throughout the year along the Chilean slopes of the Andes between 30 and 40° S. They found that the hydrological regimes of rivers north of 35° S were mostly dominated by snowmelt, whereas rivers further south (where the Andes have a lower elevation and the conditions are wetter, with rainfall distributed more evenly throughout the year) gradually shifted toward rain-dominated regimes. Analyses of the date marking the timing of the center of mass of annual flows for each water year (CT; Stewart et al. 2005) between 1961 and 2006 revealed no CT changes for almost all snowfed watersheds (14 of 15) in the northern sector, and a consistent pattern of streamflow timing toward earlier in the year (i.e., toward winter) in 22 of 25 rivers south of 35° S (Cortés et al. 2011). The fact that no changes in CT have occurred in the north despite the documented warming at high-elevation sites is interesting and contrasts with the results obtained in similar climatic regions in the Northern Hemisphere, where significant changes toward earlier streamflow timing associated with warmer temperatures have been reported for snow-dominated basins (Stewart et al. 2005; Fritze et al. 2011). Cortés et al. (2011) suggest that this situation is due to the overdominant role of precipitation on the hydrologic regimes of these snowfed basins, in which the effect of rising temperatures could be largely overridden by variability related to precipitation.

Indeed, other studies (see, e.g., Masiokas et al. 2006, 2012) have also found that variations in the regional snowpack and streamflow records are very closely linked to variations in winter and annual total rainfall in central Chile. These similarities are to be expected given the relatively simple nature of the hydrological system of this region, which is primarily driven by moisture coming from the Pacific in a succession of westerly frontal systems concentrated during the winter months (Falvey and Garreaud 2007). This situation alleviates to some extent the problem of constructing long, representative hydroclimatic time series, as it allows the use of a relatively limited number of station records to capture the main hydrologic patterns in this region. Moreover, this offers the possibility of inferring or validating the information provided by one variable (e.g., snowpack) using data from other remaining variables (e.g., central Chile rainfall and/or Andean streamflows). Masiokas et al. (2012) further propose that it is possible to use different precipitation proxies to extend back in time the information on snowpack variations in the Andes (see discussion of their results later).

5.14.4 Relationship of Local Hydroclimatic Variations with Large-Scale Atmospheric Features such as ENSO and PDO

The significant influence that tropical Pacific Ocean–atmospheric conditions exert on the study region's hydroclimatic variability has been known for decades. In their pioneering study of the 'Southern Oscillation,' Walker and Bliss (1932) include rainfall variations in central Chile and pressure changes in Santiago among the variables used to calculate the Southern Oscillation Index (SOI) for the austral winter. Many subsequent studies have assessed the relationship between ENSO and central Chile rainfall variations (e.g., Pittock 1980; Quinn and Neal 1983; Aceituno 1988; Rutlland and Fuenzalida 1991; Montecinos et al. 2000; Montecinos and Aceituno 2003; Quintana 2004). Additional analyses have also examined the influence of ENSO on Andean snow accumulation (Escobar and Aceituno 1998; Masiokas et al. 2006, 2010) and mountain river discharges (Waylen and Caviedes 1990; Caviedes 1998; Compagnucci and Vargas 1998; Norte et al. 1998; Waylen et al. 2000; Compagnucci et al. 2000; Rubio-Álvarz and McPhee 2010; Gimenez et al. 2010; Cortés et al. 2011). Most of these studies concur that El Niño events are generally associated with wetter-than-normal conditions in the study region, whereas during La Niña years drier conditions are more likely to occur. Cortés et al. (2011) found that CT time series of Chilean rivers in snow-dominated basins were indeed strongly correlated to various ENSO indices, with the annual streamflow center of mass occurring later (i.e., toward the summer) during El Niño years because of the excess in precipitation during the cold season. In addition, various analyses of historical ENSO variations (Quinn and Neal 1983; Ortlieb 1994, 2000) have relied on the warm/wet relationship between ENSO and precipitation levels in central Chile to identify and estimate the severity of El Niño years between the sixteenth and nineteenth centuries.

Masiokas et al. (2006) quantified the association between tropical Pacific ocean–atmosphere conditions and Andean snowpack variations using seasonally averaged 2.5°×2.5° gridded sea surface temperatures (SST) and sea level pressure (SLP) time series derived from the National Centers for Environmental Prediction–National Center for Atmospheric Research (NCEP–NCAR) reanalysis global database (Kalnay et al. 1996). **Figure 4** portrays the correlation between the regional MSWE series and Jun.–Sep. (midwinter) SST and SLP averages as reported by Masiokas et al. (2006). Together with results from earlier seasons (not shown) these correlation maps indicate that the strongest associations are concentrated during the winter months and mostly over the tropical Pacific domain. This interesting finding was corroborated with multiple regression analyses in which several large-scale, seasonally averaged climatic indices such as the Niño 3.4 index, the SOI, the Pacific Decadal Oscillation (PDO), the Antarctic Oscillation (AAO), and two indices indicative of Atlantic conditions were

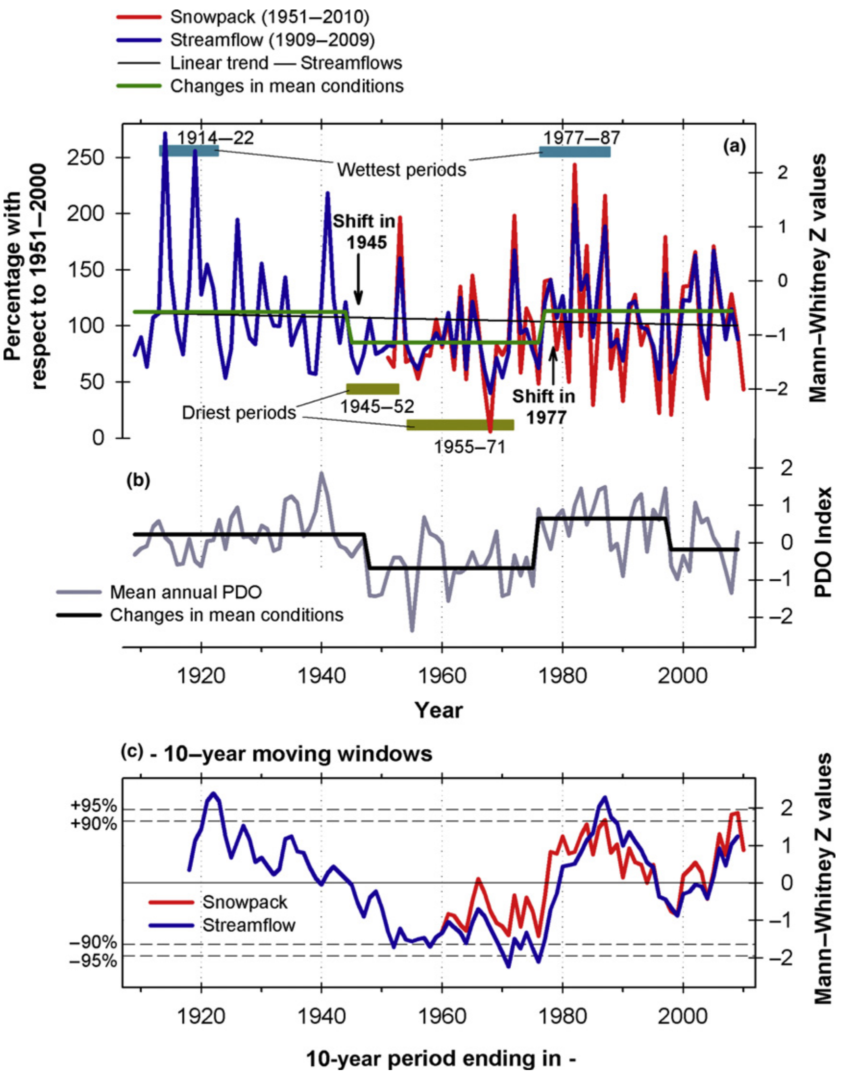

Figure 3 (a) Regional snowpack and streamflow records (red and blue lines, respectively) for the Andes of central Chile and central-western Argentina (**Figures 1 and 2**, data updated to 2009–2010 from those presented in Masiokas et al. 2010). Given the strong similarities between these records, only the temporal patterns of the longer streamflow series are shown in this figure. The least squares linear trend in regional river discharges is slightly negative but nonsignificant over the 1909–2009 interval. Regime shifts in mean flow conditions (green line) were calculated based on Rodionov (2004, 2006; refer to these references for details on this technique). Two statistically significant regime shifts were identified in 1945, when mean levels dropped 32%, and in 1977, when they increased 29%. The driest and wettest periods on record (i.e., those periods with the highest concentration of extreme high and low values in the record) are indicated by horizontal bars. These extreme intervals were determined from all possible nonoverlapping moving windows of 6–20 years in length using nonparametric Mann–Whitney tests and Monte Carlo simulations as described in Mauget (2003, 2004, 2011). Essentially this method samples data rankings over running time windows, converts those samples to Mann–Whitney *U* statistics, and then normalizes the *U* statistics to Z statistics using Monte Carlo generated null parameters. Based on the magnitude of the Mann–Whitney Z values this algorithm can identify time windows containing significant incidences of low or high data rankings. This is an objective, relatively simple, and statistically based way of detecting the driest and wettest intervals in these hydrological time series. (b) Mean values for 1909–2009 Jul.–Jun. of the PDO index (gray line) and shifts in mean regime levels (black line) identified in this series using Rodionov's technique. (c) Running 10-year samples of Mann–Whitney *Z* values as determined using Mauget's technique. Horizontal dashed lines indicate the 90 and 95% positive and negative significance determined from Monte Carlo simulations. Note the similar patterns of decadal-scale variations between the regional streamflow and snowpack records.

used as potential predictors of winter snowpack in the Andes (see Masiokas et al. (2006) for more details). The multivariate regression trials revealed that none of the seasonal values of these climatic indices for the Nov.–Apr. (early summer–late fall) period was significantly correlated with the snowpack record, and, therefore, they cannot be used as predictors of snow accumulation during winter in the Andes. In contrast, significant correlations were found between the snowpack record and the May–Jul. (early–midwinter) averages of the Niño 3.4, SOI, and the AAO indices. However, owing to intercorrelation among these variables only the SOI was included in a final regression model, which was able to explain about 44% of the variance in the snowpack record. Overall, these results present an important limitation for the prediction of winter snow accumulation using data from these large-scale climatic indices from the preceding months. Given the

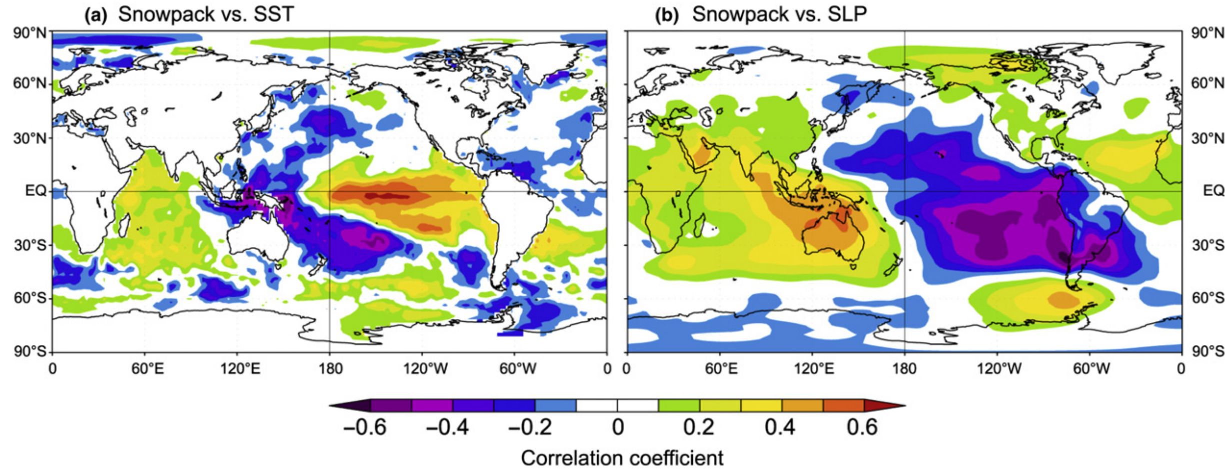

Figure 4 Correlation maps showing the varying spatial association between the regional snowpack series and seasonally averaged NCEP–NCAR reanalysis 2.5° × 2.5° sea surface temperature (a) and sea level pressure (b) gridded data over the 1952–2003 interval. The maps were created using the linear correlation and mapping routines available at the website of the Earth System Research Laboratory, Physical sciences Division, NOAA [Available online at http://www.esrl.noaa.gov/psd/data/correlation/]. Note that (a) shows the well-known ENSO-like wedge pattern over the tropical and subtropical Pacific (e.g., Trenberth and Caron 2000; Trenberth et al. 2002). Strong positive correlations occur over the Niño 3 and Niño 4 regions, and negative correlations are mostly concentrated over the subtropical western Pacific Ocean. The pattern in (b) also shows a noticeable ENSO-related structure (Trenberth and Caron 2000). Figure modified from Masiokas, M. H., R. Villalba, B. H. Luckman, C. Le Quesne, and J. C. Aravena, 2006: Snowpack variations in the central Andes of Argentina and Chile, 1951–2005: large-scale atmospheric influences and implications for water resources in the region. *J. Clim.*, **19**, 6334–6352.

socioeconomic importance of the Andean snowpack, improved predictive skills are desirable and more research is needed to identify better predictors of snowpack records from atmospheric variables or climatic indices from the period prior to the austral winter (e.g., McCabe and Dettinger 2002). Since the most serious challenges in managing the mountain water supply will likely occur during below-average snowfall years, special attention should also be paid to those large-scale atmospheric linkages associated with (or leading to) extreme dry years in the Andes. Masiokas et al. (2006) proposed the development of predictor series based on a north–south index utilizing SLP or geopotential height data from the subtropical Pacific off the coast of central Chile combined with those from the Amundsen–Bellingshausen Seas (Am–Be) in the southeast Pacific (Figure 4(b)). Blocking activity in the Am–Be area is strongly associated not only with ENSO variability (Renwick 1998) but also with snowpack high and low values in the Andes (see later). A better understanding of additional atmospheric teleconnections affecting conditions in the southeast Pacific (e.g., Jacobs and Comiso 1997; Marques and Rao 1999) may lead to improved predictive skills for estimating winter snowpack conditions in this region. Some studies have reported results that provide promising perspectives to tackle this issue. Berri and Flamenco (1999) found strong correlations between October and March streamflows of Río Diamante (station d in Figure 1) and the previous Mar.–Apr. and concurrent Nov.–Dec. Niño 3 SSTs and used this relationship to develop a multiple linear regression model of warm season surface runoff in this basin. More recently, Gimenez et al. (2010) used the winter values of the Multivariate ENSO Index (MEI) and snowpack data to predict Río San Juan streamflows (station a in Figure 1) at a 6-month lead time.

Enhanced blocking activity over the Am–Be area in the southeast Pacific is a known ENSO-related atmospheric teleconnection occurring during El Niño events (Karoly 1989; Renwick 1998; Kiladis and Mo 1998). In 1991, Rutlland and Fuenzalida and subsequently Montecinos and Aceituno (2003) reported that this enhanced blocking activity was closely related to above-average winter rainfall totals in central Chile. Masiokas et al. (2006) investigated the influence of these tropospheric circulation anomalies on Andean snowpack variations using peak winter (Jun.–Sep.) mean 500-hPa geopotential heights derived from the gridded NCEP-NCAR reanalysis dataset of Kalnay et al. (1996). For the 10 snowiest years Masiokas et al. (2006) found extensive and well-defined regions of averaged positive height anomalies (associated with enhanced blocking activity) concentrated between 60–70° S and 90–120° W in the Am–Be area and a concurrent weakening of the subtropical Pacific anticyclone around 30 and 40° S and 130 and 150° W (Figure 5(a)). Interestingly, the 10 driest years on record corresponded with an almost exactly opposite anomaly pattern, with negative winter 500-hPa geopotential height anomalies over the Am–Be region and positive anomalies in the subtropical South Pacific between 25 and 40° S (Figure 5(b)). These results confirmed the findings of previous studies (e.g., Rutlland and Fuenzalida 1991) and indicate that large-scale tropospheric circulation anomalies in the mid to high latitudes of the Southern Hemisphere are indeed a very important forcing that modulates snowfall in the Andes. Based on the maps in Figure 5, it seems reasonable that an increase in the number of blocking events in the Am–Be area and a weakening of the subtropical Pacific anticyclone during winter result in a northward migration of the westerly storm tracks, and above-average precipitation totals in the study area. The remarkably similar height anomaly pattern of opposite sign for the driest years (Figure 5(b)) suggests that a stronger Pacific anticyclone and depleted height anomalies in the SE Pacific during winter determine a southward displacement of westerly

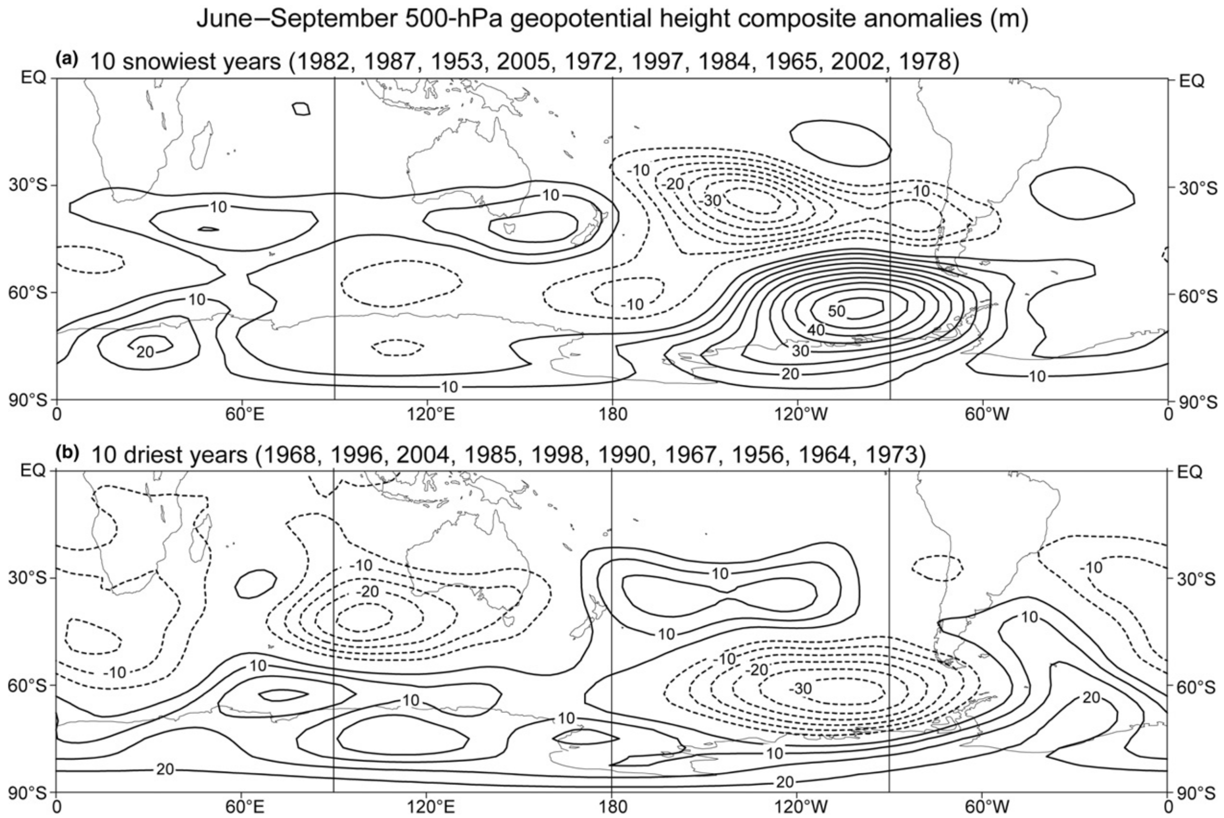
June–September 500-hPa geopotential height composite anomalies (m)
(a) 10 snowiest years (1982, 1987, 1953, 2005, 1972, 1997, 1984, 1965, 2002, 1978)
(b) 10 driest years (1968, 1996, 2004, 1985, 1998, 1990, 1967, 1956, 1964, 1973)
EQ
30°S
60°S
90°S
0
60°E
120°E
180
120°W
60°W
0
-10
-20
-30
10
20
30
40
50

Figure 5 (a) Jun.–Sep. mean 500-hPa geopotential height anomalies for the 10 snowiest years in the central Andes as identified by Masiokas et al. (2006) for the period 1951–2005. Mean monthly gridded data were obtained from the NCEP/NCAR reanalysis global dataset (Kalnay et al. 1996). Contours are in meters with a 5-m contour interval, and zero lines are omitted. Positive (negative) contour anomalies are shown as solid (dashed) lines. (b) Same as (a), but for the 10 driest years in the central Andes. The maps were created as follows: for each event year and grid point, mean peak winter (Jun.–Sep.) height anomalies from the 1968–1996 reference period were calculated from monthly data and subsequently averaged to create separate composite 500-hPa height anomaly maps for the 10 snowiest and driest years on record. Figure slightly modified from Masiokas, M. H., R. Villalba, B. H. Luckman, C. Le Quesne, and J. C. Aravena, 2006: Snowpack variations in the central Andes of Argentina and Chile, 1951–2005: large-scale atmospheric influences and implications for water resources in the region. *J. Clim.*, **19**, 6334–6352.

air masses with the resulting reduction in snowfall in the Andes (Masiokas et al. 2006).

As mentioned earlier, Masiokas et al. (2010) focused on the main IMD patterns in the snowpack and streamflow records. They found that the inception of the driest period of the twentieth century in this portion of the Andes was roughly coincident with a shift toward extended negative conditions in the PDO in the mid-1940s (e.g., Mantua et al. 1997; Mantua and Hare 2002; **Figure 3(a) and 3(b)**). The shift toward wetter conditions in 1977 in the Andes also corresponds with a very well-known regime shift toward more positive PDO levels in 1976–1977. Despite some discrepancies between the regional streamflow record and the PDO (especially noticeable on a year-to-year basis, **Figure 3(a) and 3(b)**) the occurrence of these relatively synchronous regime shifts in the 1940s and 1970s led Masiokas et al. (2010) to suggest that the slowly evolving patterns of the PDO may have influenced the IMD hydrologic behavior at these latitudes in the Andes. The correspondence observed between the extended ‘cool’ PDO levels between 1944 and 1976 and the below-average winter snowpacks and annual discharges recorded during this interval (**Figure 3**) resembles the relationship between cool ENSO events and dry conditions in the Andes discussed in the literature. Likewise, the wetter hydroclimatic conditions recorded in the Andes after 1977, concurrent with a ‘warm’ phase of the PDO, also resemble the warm–wet relationship discussed above in relation to the impacts of ENSO in this portion of the Andes (see, e.g., Rutlland and Fuenzalida 1991; Masiokas et al. 2006). Dettinger et al. (2000) found a similar, consistent pattern of positive correlations between streamflow data from the study area and interannual and decadal ENSO-like climatic variations across the Pacific. However, whether these cool–dry/warm–wet relationships are entirely valid at the longer timescales characteristic of the PDO remains uncertain, and further research is needed to clarify this interesting issue.

5.14.5 Reconstructing Andean Snowpack Variations from Multiple Proxies

Masiokas et al. (2012) developed two complementary reconstructions of Andean snow accumulation covering the past two to eight centuries. The evidence used to develop and validate these snowpack reconstructions includes instrumental rainfall

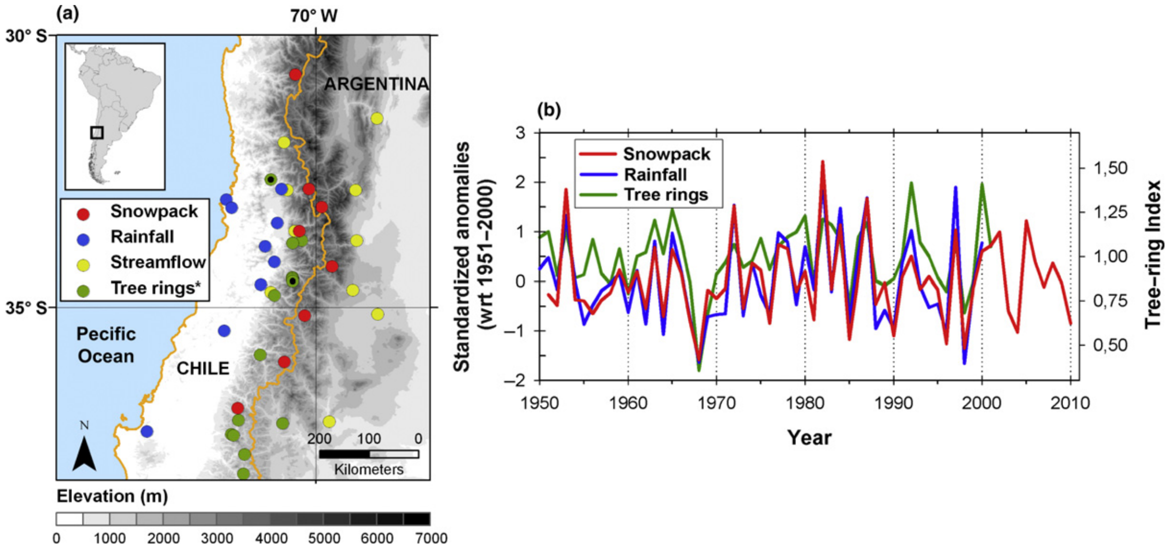

Figure 6 (a) Location of snowpack, rainfall, streamflow, and tree-ring sites used in the reconstruction of snowpack as described in Masiokas et al. (2012). Note (*): from the available network of tree-ring sites (green dots), the two tree-ring chronologies finally selected in the reconstruction model are marked with a black dot. (b) Comparison of the regional records of Andean snowpack and winter rainfall in central Chile, and the mean tree-ring index of the two selected chronologies as mentioned earlier. The resemblance between the snowpack and rainfall series is remarkable. The tree-ring series from these precipitation-sensitive trees also shows strong similarities with the instrumental records. The figure shows the 1951–2010 period covered by the snowpack series, but the regional central Chile rainfall series covers the period AD 1866–2000 and the tree-ring series goes back to AD 1150. The snowpack and rainfall series are expressed as standardized anomalies from the 1951–2000 period, whereas the tree-ring series is adimensional. See text for more details. Figure modified from Masiokas, M. H., R. Villalba, D. A. Christie, et al., 2012: Snowpack variations since AD 1150 in the Andes of Chile and Argentina (30°–37° S) inferred from rainfall, tree-ring and documentary records. *J. Geophys. Res.*, **117**, D05112, doi: 10.1029/2011JD016748.

and streamflow data from adjacent lowlands, a variety of documentary records, and century-long tree-ring series of precipitation-sensitive species from the western side of the Andes. All these records share a common regional hydroclimatic signal (**Figures 2 and 6**) largely because of this region's particular and relatively simple hydroclimatic regime, with the moisture mainly coming from winter frontal systems of Pacific origin. Masiokas et al. (2012) argue that these different hydroclimate records can be used as snowpack 'proxies' for the development and independent validation of reliable snowpack reconstructions covering periods prior to 1951 when instrumental snowpack data are first available. Rainfall data from central Chile (very strongly correlated with snow accumulation values in the adjacent mountains) were used to extend the regional 1951–2010 snowpack record back to AD 1866. Subsequently, snow accumulation variations since AD 1150 were inferred from precipitation-sensitive tree-ring width series. The reconstructed snowpack values were validated with independent historical and instrumental information, including (1) documentary accounts of snow conditions over the main Andean pass between 1760 and 1890 (Prieto et al. 1999a), (2) newspaper-based records of snow depth along the main Andean pass between AD 1885 and 1996 (Prieto et al. 2000, 2001), (3) documentary accounts of the discharge of the Mendoza river (and other rivers) in the Argentinean piedmont between 1600 and 1960 (Prieto et al. 1999b), (4) the compilation of evidence for wet years in central Chile used by Ortlieb (1994) to infer the severity of El Niño events between AD 1535 and 1900, and (5) a record of total monthly hours of rain in the city of Santiago de Chile for the period 1824–1850 (Taulis 1934). Masiokas et al. (2012) assumed that the duration of the rainfall events during winter is very likely positively correlated with the amount of precipitation received in the lowlands of central Chile and in the adjacent mountains to the east. Thus, extended periods of rain in Santiago during the winters of 1824–1850 should correspond with higher-than-normal snow accumulations in the Andes, and vice versa.

According to Masiokas et al. (2012), the verification tests performed on the snowpack reconstructions offer some confidence in the reliability of these reconstructed time series. However, the authors indicate that because of the varying nature of the proxy data available, the resulting reconstructions contain certain characteristics that can be considered as either strengths or limitations depending on the needs of the end users of these data. For example, the first reconstruction approach, based on central Chile rainfall data, showed exceptional skill for modeling Andean snowpack variations (84% of variance accounted for by the model over the 1951–2000 calibration period; Masiokas et al. 2012). However, this reconstruction was restricted to the period after AD 1866 by the length of the instrumental records (**Figure 7**). The high quality of this first reconstruction could be very useful, however, for local water resource managers, decision makers, and stakeholders interested in long, highly reliable mountain snowpack data as a basis for infrastructure planning and for developing a better understanding of Andean hydroclimatic variability over the past 150 years. In contrast, the tree-ring based reconstruction model was less accurate in modeling the instrumental snowpack record over the calibration period (45% explained variance and higher associated uncertainties than the other model; (Masiokas et al. 2012)). Nevertheless, the resulting reconstruction offers the unique possibility of assessing in

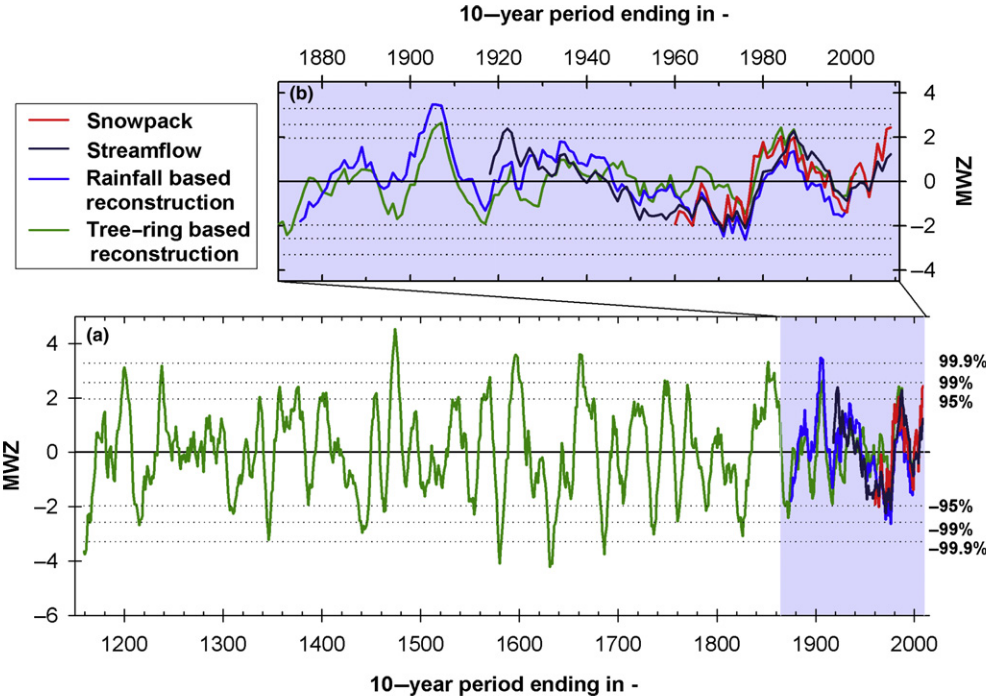

Figure 7 Comparison of the decadal patterns of variations in instrumental snowpack and streamflow records (red and dark blue lines, respectively), with those of the rainfall-based and tree ring-based snowpack reconstructions (blue and green lines, respectively) recently developed by Masiokas et al. (2012). As in **Figure 5(c)**, here, Mann–Whitney Z statistics for running 10-year samples of each original series are shown. (a) Period covered by the tree ring-based reconstruction (AD 1150–2001). (b) Period since AD 1866 covered by the rainfall-based reconstruction. Horizontal dotted lines indicate positive and negative significance at the 95, 99, and 99.9% confidence levels derived from Monte Carlo simulations. In this case, 10-year windows reaching these levels would be considered statistically wetter or drier than expected under essentially stationary conditions (see Mauget 2011 for details on the methodology). Note the overall similarities of decadal variations between the instrumental and reconstructed series. Reproduced from Masiokas, M. H., R. Villalba, D. A. Christie, et al., 2012: Snowpack variations since AD 1150 in the Andes of Chile and Argentina (30°–37° S) inferred from rainfall, tree-ring and documentary records. *J. Geophys. Res.*, **117**, D05112, doi: 10.1029/2011JD016748.

a quantitative and objective manner the history of snowpack fluctuations over the past 850 years in this Andean region (Figure 7). This reconstruction represents the first annually resolved mountain snowpack reconstruction covering most of the past millennium in the Southern Hemisphere. According to Masiokas et al. (2012), the lower skill of the tree ring-based model is very likely due to the differential tree-growth response to extreme dry vs. extreme wet or snowy conditions: as with other precipitation-sensitive tree-ring species, the chronologies usually reflect the dry to extreme dry conditions better than extreme wet years for which the soil moisture content exceeds the physiological needs of the trees (Fritts 1976).

Masiokas et al. (2012) used the same approach used in 2010 for assessing the main IMD modes of variability in the snowpack reconstructions. This technique had already been used in other instrumental hydroclimatic records (Mauget 2011) but is novel in paleoclimatic studies. The approach offers very promising perspectives for identifying the most extreme intervals in a given time series while testing their statistical significance in a simple and objective manner. The timing and significance of the intervals with the highest and lowest values detected by the running MWZ method (Mauget 2011) for each window length were recorded and tested collectively to identify the driest and snowiest periods in the reconstructed time series. The results provide a very useful reference for assessing the relative significance of recent conditions in a long-term context, and can also be used to evaluate the extent and magnitude of historic droughts and snowy periods in this region. Figure 7 shows that in general the instrumental and reconstructed time series show broad similarities using a 10-year period as a reference. This was somewhat expected in the rainfall-based reconstruction, but the similarities with the tree ring-based reconstruction are interesting and suggest that despite the inherent limitation of this reconstruction in capturing extreme high snowpack values (see earlier discussion), the overall decadal-scale regional patterns of snowpack variations are still represented relatively accurately in this time series. This information could be useful for both local water resource managers and ongoing modeling analyses intended to predict decadal climate patterns (Meehl et al. 2009; Keenlyside and Ba 2010), which are of more direct relevance to society than the more distant, highly uncertain centennial-scale climate projections generally discussed in the literature. However, it should be noted that only those models that accurately simulate (hindcast) the statistics and the inherent variability observed on the instrumental hydroclimatic records and on the most relevant atmospheric and ocean circulation features will provide a solid basis for the assessment of future vulnerabilities and the development of adaptive strategies to increase resilience.

These main temporal patterns identified in the reconstructions can also provide relevant, quantitative information for larger scale studies involving the main factors affecting the hydroclimate in this portion of the Andes. Besides the well-known influence of ENSO in this region, recent analyses have also identified a potential influence of the PDO on the low-frequency modes of variability in the snowpack and streamflow records of this region (Masiokas et al. 2010; see also Dettinger et al. 2001). The long Andean snowpack reconstructions presented by Masiokas et al. (2012) allow an assessment of the strength and time stability of the relationships with ENSO and the PDO over most of the past millennium and may complement the great number of studies (e.g., Stahle et al. 1998; Cobb et al. 2003; MacDonald and Case 2005; D'Arrigo et al. 2005; D'Arrigo and Wilson 2006; Gergis and Fowler 2009) that discuss the regional manifestations and long-term variability of these large-scale ocean–atmosphere features.

5.14.6 Climate and Hydrological Sciences Informing Vulnerability Reduction and Adaptation

The term 'vulnerability' can be defined as the degree to which a system, such as a rural community or agricultural producer, is susceptible to the adverse effects of stressors and change (Smit and Wandel 2006). Given the exposure of a community or agricultural producer to climatic hazards and their impacts, vulnerability results from an equation involving the sensitivity the degree to which a system is affected by climate-related stimuli and the adaptive capacity the ability of a system to adjust to climatic risks and opportunities by increasing its coping range. Both sensitivity and adaptation are related to variables such as natural, human, social and institutional capital, economic resources, and infrastructure. Climate exposures articulate with others from economic and social spheres, composing double exposures (Leichenko and O'Brien 2008). Vulnerabilities are also unequally distributed in space and in relation to different social groups or actors. They could come not only from these exposures but also from undesired effects of adaptive practices, as one's adaptation practices may cause increasing vulnerabilities in others (Montaña 2011).

The Río Mendoza basin is a very interesting case study because it expresses well the different vulnerabilities to sustained water deficits. Although all agricultural producers are vulnerable to droughts, the degree to which these producers will be affected by this natural phenomenon will depend on their productive system. For example, producers of crops that are relatively resistant to water stress, such as vine growers, are inherently less vulnerable to water deficits than horticulture producers, which are entirely dependent on a certain watering frequency. Likewise, large-scale capitalized producers from both vine and horticultural productive systems, who have access to high technology irrigation systems and who are able to drill wells and pump groundwater according to their needs, are obviously less vulnerable to fluctuations in surface runoff from mountain rivers than the smaller scale producers whose subsistence is entirely dependent on water distributed through surface irrigation. There are also double exposures, as the vulnerability of the smaller producers has already been increased by previous exposure to the dominant globalized agribusiness, in a vicious circle of increasing sensitivity to droughts and decreasing capacities to adapt to this phenomenon. Likewise, vulnerability to droughts depends on location. Producers located upstream or near the sources of water tend to be less sensitive to droughts than those located downstream from urban centers or at the far end of the irrigation network. The more favorable locations are accessible only to producers with enough capital to acquire these more expensive oases lands or to those able to start new farms in the natural dry shrublands along the Andean piedmonts that require significant investments in land cleaning, leveling, well construction, pressurized irrigation systems, etc.

Extreme hydroclimatic events such as extended droughts will only consolidate or accelerate the existing tendency toward a spatial and socioeconomic segregation of the agricultural producers of the oases in central-western Argentina, widening the gap between the dominant players of the local agri business and those who are barely able to survive as subsistence producers. In many cases, these small-scale producers will have to neglect their farms to work on a salary basis for large-scale companies or even be forced out from the agricultural sector and migrate to cities, where they will join the growing number of urban poor. Scenarios of increasing water deficits suggest an intensification of the current process of transformation of the socioeconomic and agricultural structure of these hydraulic societies along the eastern side of the Andes (Montaña, 2011).

Interestingly, the degree of vulnerability of the different players in this hydraulic society may change considerably based on specific adaptive practices. The flows of Río Mendoza have been recently regulated to reduce seasonal and interannual variability in the river discharge and to compensate for spring and autumn water deficits in crops. As several studies have projected an earlier onset of spring snowmelt in response to potentially future warmer conditions in high-elevation regions, this may result in reduced vulnerabilities to potential changes in the seasonal supply of water, ultimately producing only minor impacts on the local agricultural system. However, given the spatial distribution of agricultural lands and the less favorable, scattered location of goat breeders in the drylands downstream from the main users of the Río Mendoza waters, all positive effects that regulation provides to the agricultural oasis will work against the delivery of flows to the distal part of the basin. As these regulations do not ensure ecological flows, a more intense and regulated use of water upstream by the social groups with highest power clearly reduces the possibilities of water 'escaping' to the downstream part of the basin where desert communities are settled. This evident inequity constitutes an interesting case in which a particular set of adaptive practices benefit some sectors but considerably increase the vulnerability of other groups. Although their subordinate social position largely determines the sensitivity of these poor rural communities to various economic and environmental factors, extended droughts will ultimately be the trigger for increased conflicts in this hydraulic society.

The recent findings on the spatiotemporal patterns of mountain snowpack and streamflows provide a new perspective for a better understanding of vulnerabilities in these dryland, coupled human and natural systems. In a social research context, these findings offer the possibility of contextualizing contemporary droughts and their socioeconomic impacts in a long-term perspective. For example, the relative magnitude of the 2004–2005 drought, locally perceived as severe, can now be revaluated in the light of the existing snowpack and streamflow time series. This new evidence indicates that such extreme dry years are not as uncommon as initially believed. This may in turn help raise awareness of the possibility that harsher and longer droughts will occur in the future, and encourage appropriate adaptation measures.

A better understanding of the functioning of these coupled natural and social systems, and the possibility of linking the occurrence of dry and wet periods over the past century with the evolution of recent crises in local agricultural economies, may also offer the very interesting opportunity of exploring the balance between 'social' and 'natural' factors involved in these particular crises. This integrative assessment could be approached by focusing on the local economic effects of particularly dry or wet years and the ENSO impacts in this region, or by focusing on longer timescales where intra- to multidecadal dry or wet periods (which appear to be modulated by the PDO, see earlier) may have also affected the evolution of certain favorable or unfavorable economic cycles in these societies.

The existence of long, reliable hydroclimatic time series and strong, time-stable correlations between Andean snowpack and river discharges with central Chile rainfall and Pacific SSTs constitutes a possible early warning tool that may help anticipate the occurrence of droughts in the eastern foothills of the Andes. This information is also crucial for a detailed testing and validation of results from global and regional climate and hydrological models. Only models that accurately simulate (hindcast) the statistics and the inherent variability observed on the hydroclimatic records and on the most relevant atmospheric and ocean circulation features will provide a solid basis for the assessment of future vulnerabilities and the development of adaptive strategies to increase resilience. With these caveats in mind, various measures to rationalize the water resources and accommodate agricultural practices could be taken based on this information. Other strategies involving longer timescales for planning and development of major projects and investments (e.g., major hydraulic infrastructure such as dams) may in turn be decided taking into account robust modeling results and the inherent multidecadal patterns of fluctuations observed in Andean hydroclimatic records. For example, the construction of the Potrerillos dam in the Río Mendoza basin took almost a century from the first proposal of the project. Increased awareness of the recent past, present, and possible future behaviors of the Andean hydroclimatic system could help shorten the decision times and promote cost-effective measures for better management of the water resources. Whether in the case of purely empirical hydrological research or in a comprehensive socioeconomic vulnerability assessment, the mere existence of the long-term Andean snowpack and streamflow data for these river basins constitutes an important step toward reducing the inherent uncertainties associated with climate scenarios currently available from global climate models and opens the possibility of formulating adaptive strategies based on a more site-specific, 'bottom-up' approach.

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5.15 Natural Hazards Assessment in Mountainous Terrains of Europe: Landslides and Flash Floods

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5.15.1 Introduction

Although much of the available information on the European mountain environment relates to the Alps, Europe has a great variety of mountain regions, from Scandinavia to Mt. Etna in Sicily and from the vast Spanish sierras to the densely wooded Carpathians. There is no standard definition of a mountain on the European scale, and national definitions vary considerably. Price et al. (2004) delineated the European mountainous areas by using topographical criteria related to altitude and steepness. According to this methodology, Europe's mountains cover 19% of the continent. The proportions of the mountainous areas vary considerably across the continent: mountains occupy 15% of the area of northern and western Europe and 24% of eastern and southern Europe. A map of the Europe's mountain area based on the above-mentioned criteria is reported in **Figure 1**. The figure clearly reveals the great differences between the high mountains – Alps, Pyrenees, and many other mountains of the Iberian Peninsula, the Romanian Carpathians, southern Bulgaria, and Southern Fennoscandia – and the lower 'middle' mountains that account for a much greater proportion of the total area of the mountains in Europe.

The European Environment Agency (2002) report on the Alpine region recognizes the European mountains as the continent's ecological backbone. Europe's mountains are of vital importance to the continent's population in several ways. These areas are the continent's 'water towers' supplying much of the continent's water, especially in summer, and are sources of hydroelectric power. A comparison between the proportion of discharge that can be expected on the basis of catchment size and the actual discharge measured demonstrates the hydrological significance of the mountainous areas. As an example, with a mean contribution ranging from 26% (Danube) to 53 % (Po) of the total discharge, the Alps supply up to two to six times more water than might be expected on the basis of catchment size alone (Viviroli et al. 2007; Weingartner et al. 2007). They are also centers of diversity, both biological and cultural, and provide opportunities for recreation and tourism, based on natural attributes and cultural heritage.

A large climatic variation, with major north–south and west–east trends, is superimposed to the local climatic variations generated by the topographic gradients. This is accompanied by a great diversity of land covers. These mountainous environments are therefore very diverse at every scale, in terms of climate, ecology, economy, and other characteristics. European mountain landscapes are cultural landscapes reflecting long-term interactions of human beings with biophysical systems.

The extreme environment makes mountain areas prone to natural phenomena such as floods, landslides, rockfalls, and avalanches. Landscapes of high topographic relief and steep slopes favor lifting of the low-level unstable air and initiation of condensation processes (Davolio et al. 2009), orographically enhanced precipitation, and high rates of mass wasting and sediment transport. In this chapter, we will mainly focus on landslides, debris flows, and flash floods as typical natural hazards in European mountain terrain. These processes are often co-occurring because of the common triggering (intense precipitation) and the common favoring circumstances (steep slopes). Intense precipitation may trigger landslides, debris flows, and floods, which in some cases may be associated in the same event. Moreover, the morphology of the mountainous basins with small and steep river catchments can turn the intense runoff generation into severe devastating flash floods and flooding (Gaume et al. 2009). These events may trigger large erosion and sediment transport, and, under appropriate topographic conditions, they lead to the formation of debris flows (Rickenmann et al. 2008) including woody debris (Comiti et al. 2006).

In some cases, similar techniques are also used for the event risk management of these hazards. Precipitation thresholds are used to identify landslide/debris flows inducing precipitation events (Guzzetti et al. 2007). Precipitation thresholds are also used as flash flood diagnostic methods, which aim at assessing

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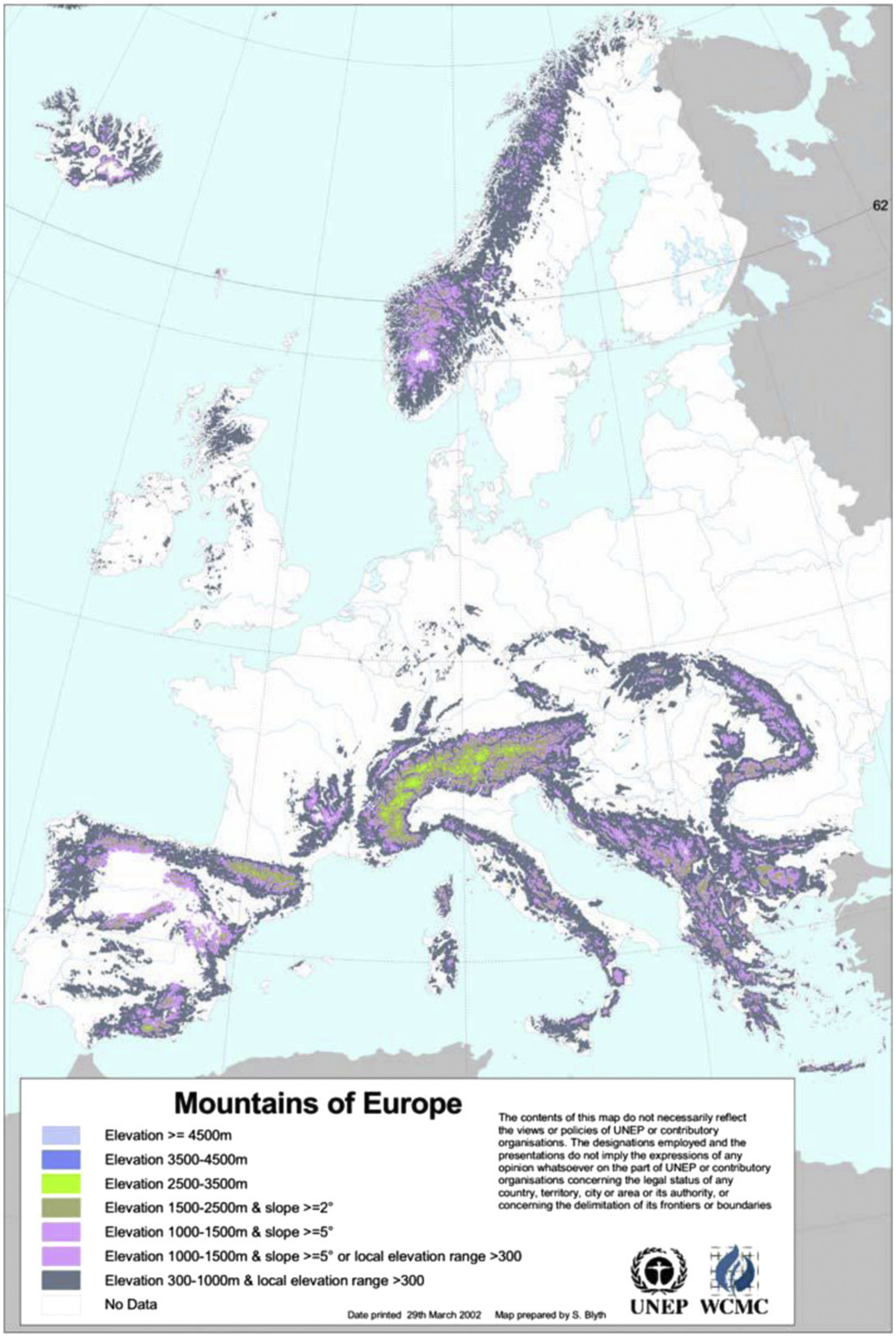
62
Mountains of Europe
Elevation >= 4500m
Elevation 3500-4500m
Elevation 2500-3500m
Elevation 1500-2500m & slope >=2°
Elevation 1000-1500m & slope >=5°
Elevation 1000-1500m & slope >=5° or local elevation range >300
Elevation 300-1000m & local elevation range >300
No Data
UNEP WCMC

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Date printed 29th March 2002 Map prepared by S. Blyth

Figure 1 Mountains of Europe. Courtesy of Nordregio, 2004: Mountain areas in Europe: analysis of mountain areas in EU Member states, acceding and other European countries. Nordregio Report 2004: 1.

the potential for flash flood at the regional scale, based on the analysis of current soil moisture status (Norbiato et al. 2008).

Landslide/debris flows and flash floods also share elements of vulnerability. For the case of debris flows and flash floods, this is typically represented by dispersed urbanization, transportation, tourism structures, as well as urbanized areas downstream of small basins. In the European terrain areas, alluvial fans represent the morphological category where flash flood/debris flows hazards and vulnerability typically overlap (see Malet et al. (2005) for an example in the French Alps). Indeed, on one hand, streamflow, debris flood, and debris flows are among the main processes contributing to the edification of alluvial fans. On the other hand, alluvial fans are historically favored building sites for human communities. Economic damages and fatalities associated with flash flood and debris flows (Guzzetti 2000; Marchi et al. 2010; Salvati et al. 2010) point to the need for better risk assessment management methodologies.

Despite being a serious natural hazard that affects regions throughout Europe, landslide, debris flows, and flash floods remain a poorly documented natural phenomenon. These events integrate processes and occur at space–time scales that are not usually covered by conventional hydrometeorological monitoring networks. Let us consider for instance the illustrative case of flash floods. The occurrence of extreme events in ungauged watersheds generally means that there is no measured discharge information or formal record of the magnitude of the event. Furthermore, data on previous flash floods are scattered among local authorities where flooding has occurred and various companies and research units that may have unpublished technical reports. These sources of information are often difficult to obtain and are generally in the national language of the country where the flood occurred. Existing inventories of past floods (Herschy 2005; Barredo 2007) include only few data on flash floods that occurred in Europe and lack quantitative information on the meteohydrological and hydraulic characteristics of the events. The lack of centralized national and international databases for storing meteohydrological, hydraulic, and socioeconomic data relating to past flash flood events within Europe hinders the development of understanding of their magnitude and occurrence (Viglione et al. 2010). Therefore, their documentation mainly relies on postevent surveys, which provide the essential, but often fragmented, observational resource (Borga et al. 2008).

Mountain geo- and ecosystems are highly sensitive to climate because of feedbacks associated with high-elevation snow cover, albedo, and heat budgets (Haeberli et al. 2007; Vavrus 2007). Temperature changes in the European Alps, for example, have increased twice as much as the global average since the late nineteenth century, and precipitation and other variables have also changed nonlinearly, with significant regional and seasonal differences, and differences by elevation and aspect (Auer et al. 2007; Haeberli et al. 2007; Brunetti et al. 2009). Changes in temperature and precipitation are considered to have a range of secondary effects, including the retreat of glaciers, the extent and duration of the snow cover, the temperature and distribution of permafrost, and the dynamics of the catchment runoff (including extremes) (Beniston et al. 2003; Vanham et al. 2008). These changes have implications on the susceptibility of triggering of both landslides and flash floods, with major consequences in both mountain areas and downstream.

This chapter provides a set of indications of landslides (see Section 5.15.2) and flash flood (see Section 5.15.3) hazard in mountainous terrains of Europe. A literature review concerning the number of fatalities due to landslide and flash floods in selected European regions complements the description. Finally, Section 5.15.4 reports the discussion and conclusion, with implication for risk management in European mountain areas.

5.15.2 Landslide Hazard in Mountain Terrains of Europe

Landslides represent a major threat to human life, property, buildings, infrastructure, and natural environments in most mountainous and hilly regions of Europe (c.f. SAFELAND 2010). Landslides are defined as the gravitational movement of a mass of rock, earth, or debris down a slope (Cruden 1991), which are basically described by two characteristics: (1) the material involved (*rock*, *rockdebris*, *earth*) and (2) the type of movement (*falls*, *topples*, *slides*, *spreads*, *flows*) (Cruden and Varnes 1996). The above classification, for example, rockfall, debris flow, and earth slide, facilitates the understanding of the failure mechanism. The occurrence and reactivation of landslides are conditioned by a number of contributing factors related to bedrock and soil properties, including slope morphology, relief energy, or land-use cover.

Currently, no comprehensive and up-to-date database of landslide occurrence and impacts exists in Europe. Inventories of landslides exist in most European countries, but access is often made difficult by restrictions and administrative and language barriers. Moreover, criteria used for the compilation differ widely from region to region. In spite of these difficulties, an interesting compilation has been carried out by the European Environment Agency (2010a), which provides an assessment of main landslide events that have occurred over the period 1998–2009 and reports the major landslide phenomena that occurred in Europe during the period 2003–2009. The report was compiled from an analysis of global disaster databases, such as the EM-DAT (2010), NatCatSERVICE (2010), and International Consortium on Landslide (ICL 2010), as well as by review of the scientific literature and the web. It is shown that the different sources of information varied significantly in their representation of the problem.

The distribution of landslide hazards over Europe is strongly linked to the geological and relief conditions of the continent. Owing to these reasons, mountainous areas, such as the Scandinavian Peninsula, the Alps, and the southern part of Europe, are most prone to landslides. Central Europe is only marginally affected, as is eastern Europe with the exception of Romania and Bulgaria (Jelínek et al. 2007; Schweigl and Hervás 2009).

For the period 1998–2009, almost 70 major landslides were recorded in different databases in Europe. These events, which often occurred at multiple sites for the same triggering factor, claimed a total of 312 lives and damaged or destroyed an extensive amount of infrastructure including roads and houses. From the analysis of the data, no obvious trend emerges in terms of landslide impacts. It is noted that potential impacts are often aggravated by land-use management including uncontrolled urbanization.

According to the report by the European Environment Agency (2010a), most catastrophic landslides in Europe are associated with heavy and/or prolonged rainfalls, coupled with soil erosion on mountain slopes (Hervás 2003). It is therefore interesting to analyze the minimum rainfall depths/rates (rainfall thresholds) required to initiate the slope instability in the various European countries. Guzzetti et al. (2007) revised the rainfall thresholds for landslide initiation for the mountainous regions included in the Central European Adriatic Danubian South-Eastern Space (CADSES) area. The work is based on a database of 853 rainfall events that resulted or did not result in landslides in the CADSES area for the period 1841–2002, with the majority of the events in the period 1954–2002. For each event, the collected information includes (1) location of the area affected by the rainfall and landslide event, (2) rainfall conditions that resulted (or did not result) in the slope failure, (3) type and number of the triggered landslides, (4) main rock types cropping out in the region, and (5) climate information. Guzzetti et al. (2007) used the rainfall, landslide, and climate information stored in the archive to identify the rainfall thresholds for the initiation of landslides in the CADSES area (**Figure 2**). In the intensity–duration plot shown in **Figure 2(a)**, rainfall conditions that resulted in landslides (663 events) are shown by filled symbols and rainfall conditions that did not result in slope failure (190 events) are shown with open circles. Despite considerable scattering and clustering at specific durations, a clear trend exists in the data. With increasing rainfall duration, the minimum intensity likely to trigger slope failure decreases linearly in the log–log plot. The self-similar behavior is clear for at least three orders of magnitude of rainfall duration, that is, from less than 20 min to about 12 days. Next, in **Figure 2(b)**, each line shows the probability that a percentage of the known landslide events lies below the line. Finally, a Bayesian approach is used to define the threshold model for likely landslide occurrence and to permit its calibration in a reasonably objective manner, and the results are shown in **Figure 2(c)**. The minimum level of intensity duration required to initiate landslides can be well approximated by the following equation:

$$I = 0.1 + 8.5D^{-0.65} \tag{1}$$

where I indicates the rain rate in millimeters per hour and D indicates the rainfall duration in hours.

Local and regional rainfall thresholds such as those developed by Guzzetti et al. (2007) may be used for operational landslide warning systems, under the assumption that future landslide events are subject to the same controls as past events. This assumption may be challenged if weather patterns change. Changes in temperature and precipitation are considered to have a range of secondary effects, including the retreat of glaciers, the extent and duration of the snow cover, or the distribution of permafrost. However, although there is the possibility of increased mass-movement activity, changes in activity are hardly visible in observational records.

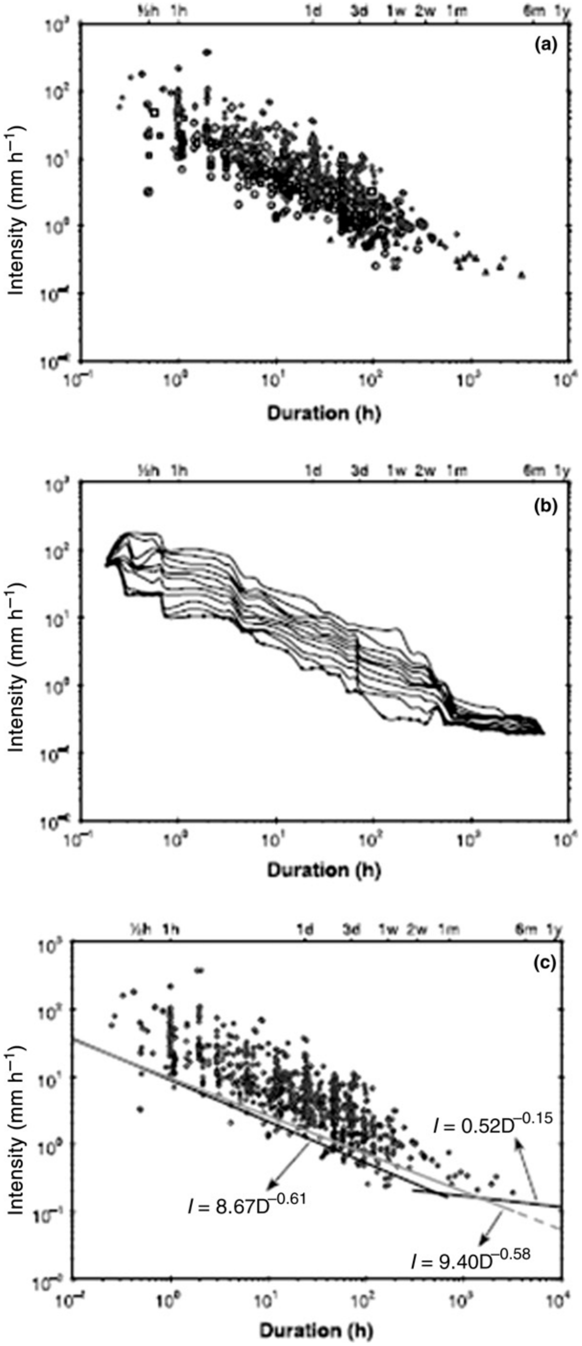


Figure 2 Rainfall intensity–duration thresholds for the initiation of landslides in the CADSES area. Source: From Guzzetti, F., S. Peruccacci, M. Rossi, and C. P. Stark, 2007: Rainfall thresholds for the initiation of landslides in central and southern Europe. *Meteorol. Atmos. Phys.*, **98,** (3–4), 239–267.

In addition to possible changes in temperature and rainfall intensity, changes in sediment supply and land use are important determinants of mass-movement frequency and magnitude. Recent observations at several sites in the Swiss Alps indicate that sediment supply can in fact change significantly as a result of permafrost degradation of rock and scree slopes or mass movements related to other processes. At the same time, with the ongoing and eventually complete downwasting of glaciers, certain sources of sediment may become depleted or disconnected from downslope systems; an increase of vegetation cover at higher altitudes could reduce erosion rates and create more stable conditions in the long term. In this case, conditions might improve and imminent hazards could decrease at certain locations on a multidecadal timescale.

Stoffel et al. (2008) suggest that, provided that sediment supply is not a limiting factor, debris flows have the potential to become larger in the future than they were in the past, but not necessarily more frequent and clearly conditioned by local site conditions (Stoffel et al. 2008; Jomelli et al. 2009; Bollschweiler and Stoffel 2010). Recent developments at high-elevation sites have shown clearly that the sensitivity of mountain and hillslope systems to climate is acute and that events beyond historical experience could occur (Goodfellow and Boelhouwers 2012).

5.15.2.1 Landslide-Induced Fatalities and Casualties

The number of fatalities (deaths and missing persons) and the number of casualties (deaths, missing persons, and injured people) are a direct quantitative measure of the intensity of a disaster and can be used to evaluate individual and social risk quantitatively (Salvati et al. 2010). Moreover, these quantities are highly relevant to landslides, debris flows, and flash floods, which correspond to high number of fatalities compared to other natural hazards. Guzzetti (2000) compiled a database of landslides that occurred in Italy between 1279 and 1999 and caused deaths, people missing, injuries, and homelessness. Analysis of the database indicates that more than 10 000 people died in a total of 840 landslide events. Fatal landslide events were more frequent in the Alpine regions of Northern Italy and in Campania (southern Italy), and most casualties occurred in the autumn. Fast-moving landslides caused the largest number of deaths. They included rockfalls, rockslides, rock avalanches, and debris flows.

5.15.3 A Large-Scale Characterization of Flash Floods Hazard in Europe

The large diversity in climate, synoptic conditions, and hydrological properties across the mountainous European terrain leads to large variability in the flash flood regimes. This heterogeneity combines with differences in social, economic, and institutional characteristics at local, regional, and national level to generate a complex pattern of impacts, responses, and mitigation policies for flash flood risk.

Marchi et al. (2010) has shown that flash floods are associated with physiographic factors that are typical of mountainous terrains. This is due to the combination of two main mechanisms: orographic effects augmenting precipitation and topographic relief promoting rapid concentration of streamflow. Both effects have been documented in the literature (Costa 1987; O'Connor and Costa 2004). Storm quasi-stationarity is a characteristic feature of several flash flood-generating rainfalls, with very intense precipitation insisting on the same locations for enough time to produce heavy accumulations. One of the elements that favors the anchoring of convective system is the orography, which plays an important role in regulating the atmospheric moisture inflow to the storm and in controlling storm motion and evolution (Smith et al. 1996; Borga et al. 2007; Davolio et al. 2009). Relief is necessary for promoting flow concentration along drainage ways, which results in high unit discharges and relevant geomorphic effects of flash floods in sloping watersheds. Heavy convective precipitation may occur also in plain areas, but the ensuing flood generally lacks the kinematic component, which characterizes the propagation and the hazard potential of flash floods.

To address the gap in available information, and particularly, to assess the possible ranges for peak discharges on small watersheds and to describe the geography of the hazard across Europe, an intensive data compilation has been carried out in the EU FP6 Research project titled 'Hydrometeorological data resources and technologies for effective flash flood forecasting' (HYDRATE, www.hydrate.tesaf.unipd.it, Borga et al. 2011). Data from seven European regions (Table 1) were considered. The data and analysis reported in this chapter update previous analyses reported by Gaume et al. (2009).

A definition of flash flood event was required as a working principle to develop the archive and select the events. An initial definition of flash flood event was based on the duration of the causative rainfall, the size of the catchment impacted by the flood, and the severity of the event. Consistent with the rules adopted by Gaume et al. (2009), the duration of the causative storm event was limited to 24 h and the maximum size of the catchment area was set to 1000 km^2. Rainstorm duration is defined here as the time duration of the flood-generating rainfall episodes, which are separated by less than 6 h of rainfall hiatus. As a follow-up, these rules were slightly relaxed to include one event with a larger catchment size (Gard event in France, 2002; with a maximum basin area of 1856 km^2).

Analysis of peak flow distribution and seasonality was carried out by collating and compiling the *primary data* on the reported flash floods. Primary data represent the minimal data structure required to qualify a flash flood event: occurrence data, location, peak discharge, and catchment area. Detailed

Table 1 Methods of estimating the flash flood peak discharges (%)

	Manning–Strickler formula estimation	*Extrapolation of calibrated stage–discharge relation*	*Hydraulic 1D simulation*	*Hydraulic 2D simulation*	*Reconstruction from reservoir operation*	*Direct current meter measurement*	*Other*	*Unknown*
Spain	56	11	33	0	0	0	0	0
France	20	33	17	0	7	0	0	23
Italy	64	23	13	0	0	0	0	0
Slovakia	0	73	0	0	0	0	27	0
Greece	66	0	0	17	0	17	0	0
Romania	0	53	0	0	47	0	0	0
Austria	0	94	6	0	0	0	0	0

precipitation data are often missing, because of the relevant estimation difficulties under flash flood conditions.

Validation of the data sets was carried out, when possible, by cross-checking reported rainfall accumulations with peak discharge estimates and identifying outliers from the rest of the data set for the region. Overall, intraregional comparisons and comparisons with other inventories did not reveal significant discordances in peak discharge estimates. The final data set includes 578 flood event records in seven European regions, as reported in Table 1, which also illustrates the methodology used for peak discharge estimation.

Although the data compilation aimed to be consistent and comprehensive in each region, the quality and quantity of data that could be collected varied from country to country, depending on the available sources of information and the institutional frameworks for collecting and recording data. The peak discharge computation methods and the corresponding discharge accuracy rate relate to the nature of the sources of information used. It can be noted that most of the discharge estimates in the catalogs for Austria, Slovakia, and Romania have been obtained from stage–discharge relationships, indicating that a large part of the data comes from gauging stations. In Italy and France, many estimates are based on hydraulic calculations, indicating that a significant proportion of the information is on ungauged sites and has been collected from scientific reports, papers, and studies. In most regions, the values closest to the envelope curve (see following discussion), correspond dominantly to ungauged sites, justifying the efforts for retrieving data from ungauged watersheds.

To enable first intercomparisons, the complete data set has been refined by selecting the most extreme events, identifying those events that are closest to the envelope curve for each region. The 30 events with the highest 'reduced peak discharge' (see next sections for a definition) were selected for each region, the reduced discharge formula being linked to the shape of the envelope curves. Several of the original data sets contained multiple records for the same rainfall event, distinguishing different peak discharge estimates at different locations within the affected catchments. In refining the data sets to 30 events, it was specified that no more than two records within the set of 30 should be of the same date in a region. This condition was selected to maintain a diversity of case studies and representativeness of the refined database.

Not all refined data sets selected meet the target number of 30 records, and the refined data set only counts 150 records over the seven considered regions (Table 2). Two indices help to compare the various data sets (reported in Table 2): the compilation coverage (watershed area multiplied by period considered) and the compilation density (number of documented events divided by the coverage). The periods as well as the areas covered by the inventories differ among regions. These features may affect the intercomparison in various ways. The number of observed events exceeding a given magnitude threshold increases on an average linearly with the considered area and period in a statistically consistent region if there is a temporal and spatial independence between events. The two conditions, consistency and independence, are not fulfilled, but the general conclusion remains valid. If we assume that the major floods have been reported in the inventory, the proportion of high-magnitude events in the 30 event sets will have a general tendency to grow with the coverage of the inventory.

This means that the Italian and Romanian inventories are more likely to contain higher-magnitude events. In contrast, this can be partly compensated by the density of the inventories for France and Slovakia; the proportion of missed extreme events, especially events that occurred on ungauged watersheds, reduces as the comprehensiveness of the inventory increases. As a consequence, the envelope curves are affected by the coverage of the inventories.

The magnitude of the most extreme floods defining the envelope curve has a general tendency to grow as the coverage grows. Likewise, the number of records close to the envelope curve increases with the density of the inventory.

5.15.3.1 Magnitude, Seasonality, and Space–Time Scales of Flash Floods in European Mountain Areas

Envelope curves provide an effective graphical summary of previous floods in a given region. They have been widely used in past publications on extreme floods (Herschy 2005; Castellarin 2007) and have the advantage of being relatively unaffected by the data compilation density because they are determined by the maximum values of a sample. Peak discharge data and the corresponding envelope curves have been plotted in Figure 3.

For the sake of clarity, a simple envelope curve equation, often used in previous studies, has been selected (eqn [2]). According to this equation, the envelopes appear as straight lines on the chosen log–log representation:

$$Q_s = \alpha A^{\beta} \tag{2}$$

Here Q_s is the unit discharge in $m^3\,s^{-1}\,km^{-2}$, A is the catchment area in square kilometer, α is a coefficient supposed to be

Table 2 Number of flash flood events listed in the HYDRATE database for each of the seven European regions

	Area (km^2)	*No. of events*	*Dates*	*Cov*	*D*	*Refined no. of events*	*Dates*	*Cov*	*D*
Catalonia	320 00	10	1962–2005	1.4	7	9	1971–2005	1.1	8
France	180 00	236	1953–2006	0.9	255	30	1953–2006	0.9	32
Italy	950 00	73	1968–2006	3.6	20	30	1968–2006	3.6	8
Slovakia	490 00	52	1995–2004	0.4	120	30	1995–2004	0.4	70
Greece	132 000	21	1960–2006	6.0	3	4	1989–2006	2.2	2
Romania	240 000	152	1973–2007	8.1	19	30	1979–2007	6.7	5
Austria	850 00	34	1987–2005	1.5	22	17	1987–2005	1.5	11

Cov, Coverage in yr10^6 km^2; *D*, density in records yr^{-1} 10^{-6} km^2.

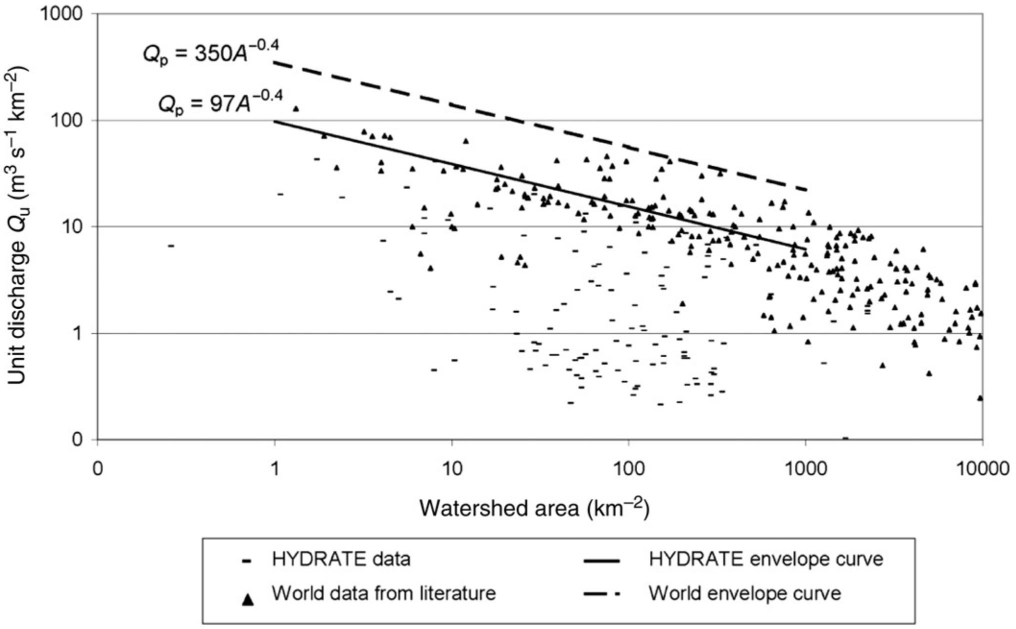


Figure 3 Comparison between the unit discharges collected for this study, HYDRATE and the unit discharges reported in literature for the world (see Gaume et al. (2009) for the definition of the world envelope curve).

independent on the catchment area also called 'reduced' discharge in $m^3\,s^{-1}\,km^{-2(1+\beta)}$, and β is a scaling exponent. As suggested by Castellarin (2007), the value of the exponent β has been estimated through a linear regression between $\log(Q_s)$ and $\log(A)$ based on each of the refined data sets. An average value of $\beta = -0.4$ appears to be the best suited to the available data sets. It lies in the range of previously calibrated envelope curve parameters for various climatic contexts (Castellarin 2007).

5.15.3.2 Flash Flood Magnitude and Occurrence

The data sets mix peak discharge estimates from watershed areas ranging from some tens of square kilometers to about 2000 km^2. According to the adjusted envelope curves and especially the value of the power β (−0.4), a reduced peak discharge Q_r has been selected as the indicator of the magnitude of the floods to aggregate the data and limit the influence of the watershed areas on the analyses: $Q_r = Q/A^{0.6}$. Q is in $m^3\,s^{-1}$; A, in km^2; and Q_r, in $m^3\,s^{-1}\,km^{-2\times0.6}$. The atlas of extreme floods over mountainous Europe thus plots the reduced discharge of events in each region (Figure 4).

The atlas maps the spatial distribution of flash floods in the seven areas included in this study. The differences appearing on this map are confirmed by examining the proportion of the flash flood events in each reduced discharge category for each considered region based on analysis of the refined data sets (Table 3). There appears to be a significant proportion of events of over 75 $m^3\,s^{-1}\,km^{-2\times0.6}$ in France (13%), northern Italy (17%), and Catalonia (11%). The lower category events ($Q_{ps} < 25\,m^3\,s^{-1}\,km^{-2\times0.6}$) represent a minority in these regions. This lower category represents three-quarters of all other inventories. This shows that Mediterranean flash floods are characterized by higher magnitude (when referred to the catchment area) with respect to the other European regions considered here.

5.15.3.3 Flash Flood Seasonal Distribution

The inventory also provides information on the patterns of seasonality of flash floods over the European regions. The number of records reported for each month is shown for each region in Figure 5 (in which events in Greece are not reported because of their reduced number). The extreme floods in Catalonia and France, without exception, occurred in autumn, whereas in the Central European countries (Austria, Slovakia, and Romania), these extremes occur only in the late spring and summer seasons. Northern Italy lies in an intermediate position with a dominant proportion of extreme floods in autumn and some in spring. This feature is not modified if the complete data set is taken into account. This difference in the seasonality shows that the most extreme flash floods in the Mediterranean and in the inland continental regions are not induced by the same types of meteorological events. Flash floods in the study area encompass a diversity of meteorological and hydrological processes.

Intense autumn storm events delivering very high amounts of rain water within a short period and sometimes over large areas appear to be a specificity of the Mediterranean area. Intense summer thunderstorms also take place frequently in this area. But they almost never induce significant floods, because of the high infiltration capacities of the dry soils in the summer season. The initial wet conditions of the watersheds can play a major role in the flash flood response to a rainfall event (Marchi et al. 2010). These conditions are linked to the climatic settings and can also explain the differences observed between the hydrometeorological regions. In the same line of thinking, Merz and Blöschl (2003) found that flash floods in

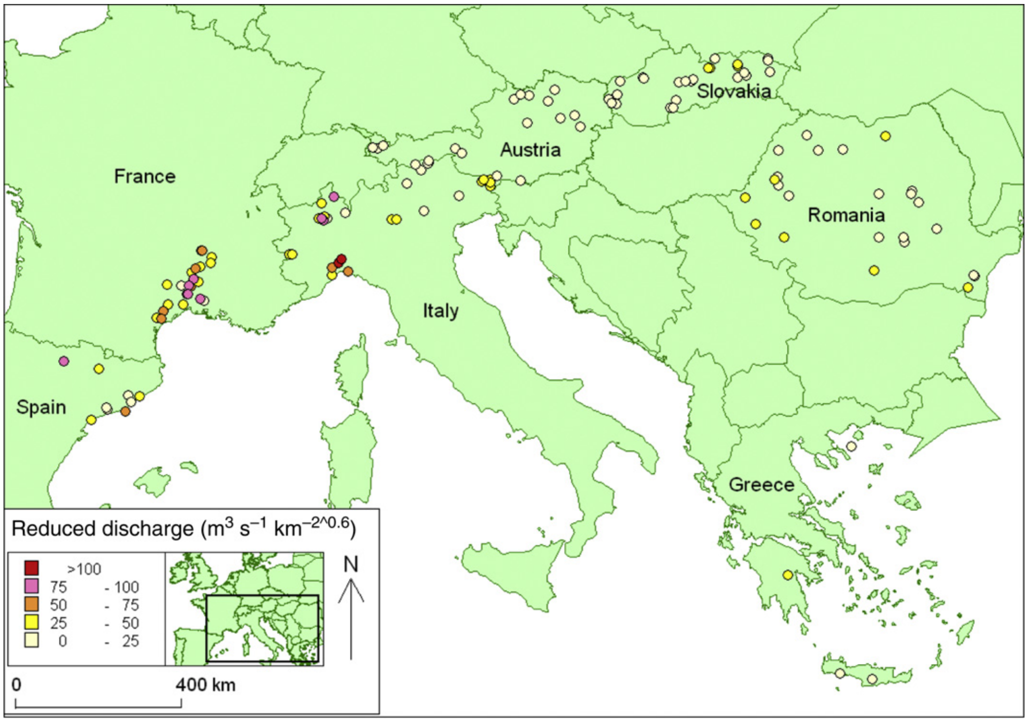


Figure 4 Atlas of reduced peak discharges of extreme events in Europe.

Austria are most extreme in the eastern part of the country, which corresponds with the flash flood atlas presented here. These authors suggested that the hilly terrain in this region increases the instability of the boundary layer and therefore increases the potential for convective storms.

5.15.3.4 Flash Flood Fatalities

The difficulties in developing homogeneous information on flash floods are also reflected in the fragmented information about flash flood-related fatalities. Among the few systematic studies with a continental view, Barredo (2007) reports a catalog of the major flood events since 1950–2006 in the European Union. In his study, he characterized major floods in terms of casualties and direct damages. Of the 47 events listed in the catalog, 23 are classified as flash floods, and are mainly localized in Italy, Spain, and southern France. Flash flood events are also reported in Germany, Belgium, and the United Kingdom. In spite of the smaller areas affected by these events, flash floods caused 2764 fatalities – that is, 52 casualties per year on an average, which is close to the annual statistic reported for the United States by Ashley and Ashley (2008).

Table 3 Proportion of events in each pseudo-specific peak discharge category in the refined data set (%)

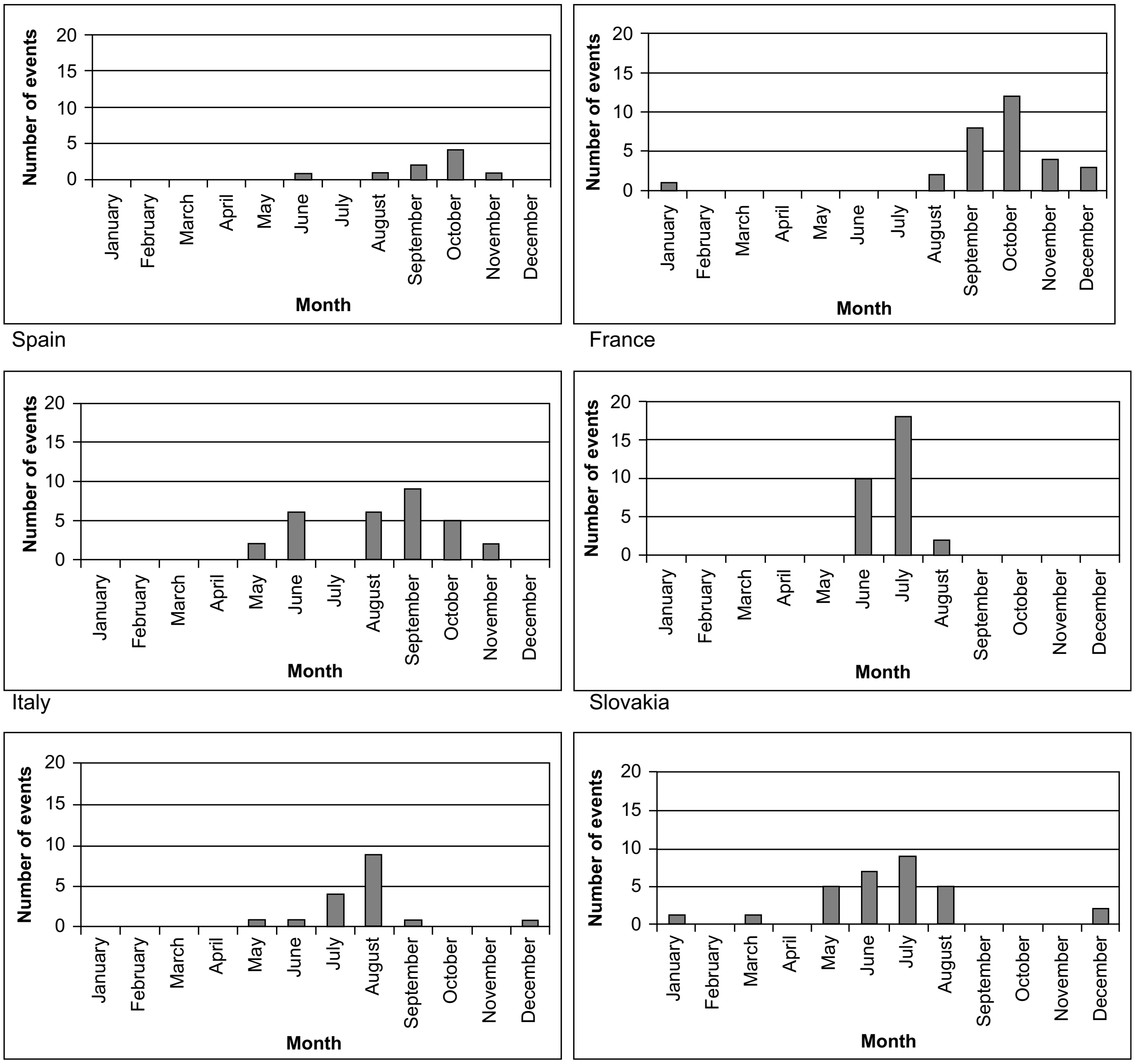
	0–25	*25–50*	*50–75*	*75–100*	*>100*
Catalonia	45	33	11	11	0
France	17	43	27	13	0
Italy	33	43	7	10	7
Slovakia	87	13	0	0	0
Greece	75	25	0	0	0
Romania	77	23	0	0	0
Austria	100	0	0	0	0

The number of flash flood-related fatalities represents 40% of the overall casualties reported in the study, largely exceeding river floods (18%), and being second only to storm-surge floods (42%). Fatalities due to storm-surge floods concentrate into three extreme events that occurred from 1953 to 1962 on the coastal regions of northern Europe, whereas flash floods have been reported over the wider period (1950–2006) and across the whole European region. It should be noted that, given the focus of the study on major events, flash flood casualties were likely underestimated by Barredo (2007).

5.15.4 Conclusions and Indication for Future Work

Landslides, debris flows, and flash floods have been examined in this chapter as natural hazards that are typical of mountainous areas in Europe. A description of the main characteristics of these hazards has been given based on catalogs obtained by integrating various sources of information.

The data catalogs mentioned in the chapter may be developed further by extending the inventories within the existing regions and also by including other countries within the database. With the introduction of the European Floods Directive in 2007 requiring the EU member states to have prepared flood risk maps by 2013, there is likely to be an increase in efforts to research and document historic floods and related hazards as part of the work done to meet the Directive. This may enable access to data that was not readily available to this study. In addition, to expand the data catalog, it may be



Spain

France

Italy

Slovakia

Austria

Romania

Figure 5 Number of flash flood occurrences in each month.

interesting to further develop the analyses of the data. This may include statistical approaches to draw intercomparisons of the data, especially to reveal the heterogeneity of the data between and within the considered regions and to evaluate the return period of the reported extreme events.

The assessment of landslides/debris flows and flash floods provides indications for risk management strategies. While warning systems can substantially assist in reducing loss to life and property, they need to be integrated into a more general framework of flood risk management. Other risk management tools are complementary to warning systems. Also, there will be instances when there is not enough warning time and people may not be reached or will ignore warnings. Similar to the forecasting and warning component, risk management should be based on a fully integrated approach that recognizes the specificities of the hazardous floods. These include (1) the difficulties to rely on traditional physical flood defense infrastructure; (2) the multihazardous nature of debris flows/flash flood risk, particularly when it involves mountainous settings; and (3) the need to develop specific preparedness strategies that incorporate event management.

The identification of debris flows/flash flood risk areas should inform the risk management process. The difficulties of relying on flood protection works place emphasis on land-use planning and flood event management. It is important to combine these two steps of risk management into one synthesized plan to enable the sharing of information between land-use planning and civil protection authorities and to exploit the synergies between these two management fields. Risk management consists of systematic actions in a cycle of preparedness, response, and recovery, and this should also be reflected in land management approaches. Long-term risk management needs to address the tensions between risk management and economic development. Embracing scenarios of the future (including climatic, demographic, and socioeconomic changes) within the decision-making process is required to identify precautionary, sustainable, and adaptable risk mitigation policies and strategies.

Accounting for the multihazard nature of debris flows/flash floods is particularly important. Often, flash floods, landslides, and debris flows occur in conjunction, which may cause amplification of the hazard – for instance, by inducing drastic changes in stream bed morphology during flash flood events. However, mapping of flood risk zones, which is an essential element in many national legislations, is generally based only on flood hazard assessment. There is therefore a need to develop a multirisk approach that can tackle possible 'simultaneous' and 'cascade' effects due to coincident, or induced, occurrence of flash floods, landslides, and debris flows that amplify the risk in some areas, and may be not accounted for by single hazard estimations.

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5.16 Flood Inundation Dynamics and Socioeconomic Vulnerability under Environmental Change

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5.16.1 Environmental Change and Its Impact on Floods

Floods are a major threat to human existence and severely affect populations across the globe (Mustafa 2007). Understanding, predicting, and mitigating the impacts of floods is thus a very important activity, but one that is rife with challenges. Floods and floodplains are dynamic and nonstationary systems. River channels and floodplains constantly change as a result of natural erosion, deposition, and channel migration processes. Additionally, they change because of external factors such as increased population pressure and demand for land for various human activities, desire for mitigating and managing floods, and climate variability and/or human-induced climate anomalies. These factors can lead to changes in flood characteristics, such as flood intensity, velocity, time to peak, and risks to which people and property are exposed (Bradshaw et al. 2007; Blaikie et al. 2004; Vojinovic and Abbott 2012).

Hazardous flooding can be defined as having too much water in the wrong place and/or at the wrong time and as such is a problem generated by humans. Excess water can occur on the land surface as a result of a variety of process drivers including extreme rainfall, river flow, groundwater emergence, dam breaks, or the combined effect of astronomical tides and storm surges. Such water *sources* are conveyed along a variety of *pathways* (as overland flow, through the subsurface, in rivers or over fluvial and coastal floodplains) to *risk receptors* where the adverse effects of flooding occur. This *source-pathway-receptor* model therefore defines the types of floods that hydrologists typically refer to: flash floods, dam break floods, fluvial or river floods, groundwater floods, and coastal floods. Flooding is therefore driven by a variety of physical processes, and it only becomes a problem when either economic damage or threats to human life, well-being, and security occur.

5.16.1.1 The Two-Faced Flood

Floods are the most common environmental hazards and cause more damage than other hazards including earthquakes, volcanic eruptions, and tsunamis (Kusky 2008). During severe weather events, flooding can be part of a *hazards complex* that includes mudslides, gales, and tidal surges that cause compound devastation (Few 2003). Floods are not just monstrous hazards that happen once in a lifetime, but their frequency and wholesale influence can affect any corner of the world, making them the worst kind. Low-magnitude high-frequency floods can lead to damage to farm land, disruption or destruction of infrastructure and facilities, suspension of

http://dx.doi.org/10.1016/B978-0-12-384703-4.00508-6

business and other activities, exposure to health risks, and so on (Few 2003). A plethora of media documents facts and figures concerning flood damage to human lives, livelihoods, and property. It is unsurprising that floods, by default, are associated with words such as *disaster*, *catastrophe*, and *hazard*, and flooding itself can thus also be defined in terms of the *potential*, *experience*, and *aftermath* of this environmental hazard (Mustafa 2007).

The nature of floods is, however, two-faced (Few 2003). Despite being perceived as a 'hazard,' humans have coevolved and coexisted with floods and floodplains. Floodplains have always been favored sites for human settlement because of their multiple functions in providing drinking water, hydropower, sites for waste disposal, fertile soils for agriculture, navigation waterways, flat terrain for building, 'waterfront' view, and leisure activities, and so on (Alexander and Marriott 1999; Bridge 2003). Floods can also bring extensive economic and environmental benefits, although often less acknowledged by people (Blaikie et al. 2003; Smith, 1996; Handmer et al. 1999; Alexander and Marriott 1999; Bridge 2003). These include habitat creation to sustain biodiversity, alluvium fertilization for agriculture, sediment mobilization and redeposition for materials exchange, and surface or subsurface water recharge and nutrient circulation. It is therefore reasonable that many residents of developing countries perceive floods with an ambivalent attitude and prefer 'living with floods' to engineering measures that prevent them (Few 2003). In fact, this is increasingly true for all people as the desire for sustainable or green living takes root in the world. Figure 1 summarizes both the hazardous and beneficial features of floods.

5.16.1.2 Climate and Flooding

Currently, one of the most politically discussed environmental changes that may affect flood dynamics and vulnerability is changes in the frequency of floods. Climate variability and longer-term change, be it artificial or natural, long- or short-term variation (Box 1), is one of the major causes of significant trends in the occurrence of flooding over time (Smith and Ward 1998). Time scales can range from short term, for example, seasonal variation, and a cluster of a number of dry/wet or warm/cold years, to decadal, centennial, and millennial variations or even multimillennial variations. Depending on the time scale and location of these changes, impacts on flooding characteristics and resulting consequences on human beings and ecosystems can be very different.

Climate-related flooding during prehistorical and early historical times has often been associated with significant impact on human settlement including field abandonment and consequent cultural adaptation (exchange, collapse, or emergence of new culture) (Fagan 2000). A number of these examples are presented in Section 5.16.3.1. The prehistorical and early historical climate variability is largely attributed to natural fluctuations of geophysical processes. This signal is now altered by human-induced climate effects. At present, our limited knowledge and understanding of Earth sciences, and the complex interactions between atmosphere, hydrosphere, and other Earth subsystems make it nearly impossible to differentiate climate-related floods caused by human-induced change from those caused by natural background variation. There is potential for intensive precipitation increases if the water holding capacity (of the atmosphere) increases with warming on a global scale (Kundzewicz and Schellnhuber 2004). This could translate into increased flood risk and vulnerabilities (Milly et al. 2002; Wilby et al. 2008; Vojinovic and Abbott 2012). A set of possible links between contemporary human-induced impacts on climate and flooding have been discussed extensively by the Intergovernmental Panel on Climate Change (IPCC) from the First Assessment Report (IPCC, 1990), through to the Fourth Assessment Report (IPCC, 2007), and the Summary for Policymakers (SPM) for

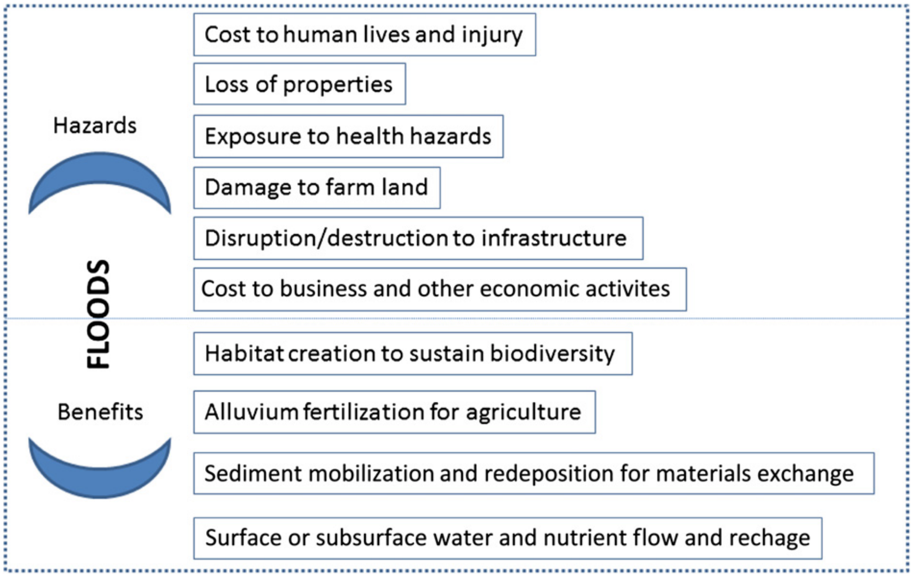
Hazards
FLOODS
Benefits
Cost to human lives and injury
Loss of properties
Exposure to health hazards
Damage to farm land
Disruption/destruction to infrastructure
Cost to business and other economic activites
Habitat creation to sustain biodiversity
Alluvium fertilization for agriculture
Sediment mobilization and redeposition for materials exchange
Surface or subsurface water and nutrient flow and rechage

Figure 1 Illustration of the 'two-faced nature' of floods bringing with them both hazards and benefits.

Box 1

Definitions of Climate Change

Climate change is defined by the United Nations Framework Convention on Climate Change (UNFCCC) in Article 1 as:

> *"a change of climate which is attributed directly or indirectly to human activity that alters the composition of the global atmosphere and which is in addition to natural climate variability observed over comparable time periods"* [United Nations General Assembly, 1992].

Climate change is defined by the Intergovernmental Panel on Climate Change (IPCC) as:

> *"a statistically significant variation in either the mean state of the climate or its variability, persisting for an extended period (typically decades or longer)"* [IPCC, 2001].

or

> *"a change in the state of the climate that can be identified (e.g., by using statistical tests) by changes in the mean and/or the variability of its properties and that persists for an extended period, typically decades or longer"* [IPCC, 2012].

UNFCCC makes a distinction between climate *change* and climate *variability*. The former is solely related to anthropogenic influence, and the latter is due to natural fluctuation of underlying physical processes. In contrast, IPCC suggests a change in climate, as long as it can be identified by statistical measures, is climate change, disregarding causes. UNFCCC does not specify the time scale of a typical climate being considered by stating *over comparable time periods*, while IPCC spells out *decades or longer*, although similarly ambiguous.

The use of the term 'climate change,' however, obscures that the fact that climate is never static, and frequencies of flood events, for example, have variations on all time scales (e.g., Rial et al. 2004). It is the total climate effect that affects the resource.

the IPCC Special Report on Managing Risks of Extreme Events and Disasters to Advance Climate Change Adaptation (IPCC, 2012).

Such studies are valuable attempts in the bid to understand the impacts of climate on flooding; however, they have two major limitations. The first lies in the highly uncertain predictions of flood risk emanating from climate models because of current unsatisfactory and patchy understanding of Earth system science, insufficient observational data, inadequate computing resources, indecisive emission scenarios, and a plethora of other subjective decisions that are involved in climate impact modeling, and translation of model results in predicted risk from climate variability and longer-term change (Reynard 2007; Hulme 2009; Beven 2011). These uncertainties in the climate impact projections on flood hazard and risk are thus from both a physical science and a human perspective not well characterized (Beven 2009), and adaptation strategies, which are often heavily based on modeled projections, may fall short and leave humans more vulnerable to flood risk. The second limitation is that, although some conclusions may be claimed for large-scale river basins (based on climate model output), it is extremely challenging to make any general conclusion for small- to medium-sized river basins or local regions (Beven 2011). Global or large-scale studies may be of less interest to adaptation because flood risk is very much location, activity, and value dependent (Swart and Vellinga 1994; Parry et al. 1996; Jones 2001) and adaptation to changing risk should be worked out within a regional or local context while also taking into consideration the responses of individual catchments. The current generation of climate models is far from being skillful in resolving small-scale physics (microphysics of convective activity, orography, and subtle but relevant feedbacks attributable to detailed topographical characteristics). Studies on climate impacts on flooding at regional and local scales remain, at best, overly ambitious exercises when based on current climate models. Section 5.16.2 reviews modeling tools that are used to study the effects of climate on floods.

5.16.1.3 Landuse Change and Flooding

Alongside climate variability and longer-term change, landuse change is the other major factor that can make humankind and ecosystems more vulnerable to flooding. Human reshaping of land cover has increased at a staggering rate. The change is *unprecedented in magnitude and rate* and has *significant impacts on the biogeochemical systems that sustain the biosphere* (William and Turner 1992). Every day more natural land is taken to be converted to an artificial state for various types of human activities and needs. Figure 2 shows an example of how much land was modified annually through human activities from 2000 to 2006 in selected European countries (The countries include Albania, Austria, Belgium, Bosnia and Herzegovina, Bulgaria, Croatia, Cyprus, Czech Republic, Denmark, Estonia, Finland, France, Germany, Hungary, Iceland, Ireland, Italy, Latvia, Liechtenstein, Lithuania, Luxembourg, Macedonia the former Yugoslavian Republic, Netherlands, Norway, Poland, Portugal, Romania, Serbia, Slovakia, Slovenia, Spain, Sweden, and Turkey). The overall area that was created during this period came up to 111 788 ha year^{-1}.

It is clear that world population growth is the driving force behind the accelerated landuse change (Box 2).

Of all land cover modification, floodplain development is of particular concern, as the frontline of defense against flooding has been largely compromised. In addition to the benefits of living on or near floodplains, rapidly increasing population leaves humankind no choice but to occupy more of the floodplains. Floodplains have precisely the function that their name suggests that rivers can be expected naturally to flow beyond their banks every few years (Wheater and Evans 2009). Floodplains provide natural storage and dampened release for excessive water and would only constitute a 'hazard' when

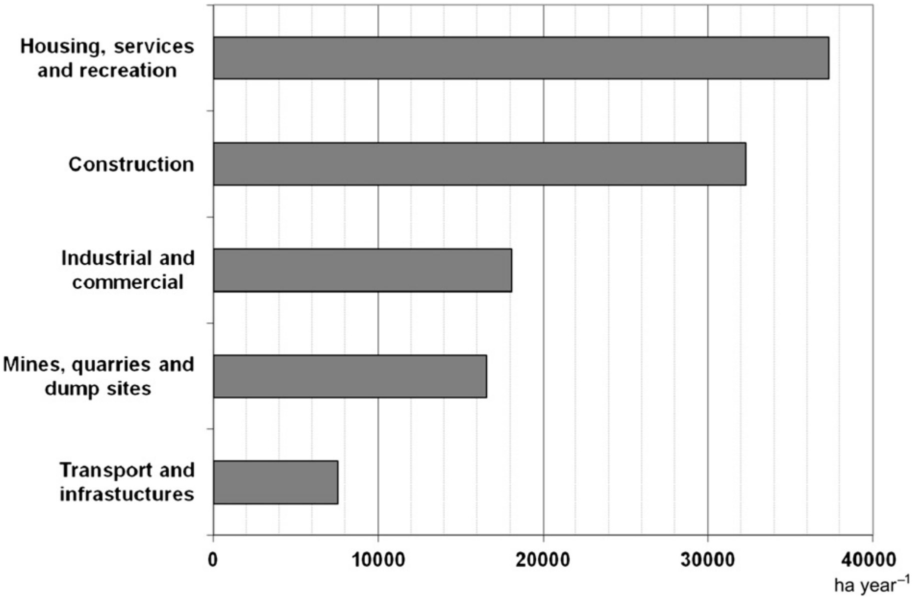

Figure 2 Annual land (hectares per year) taken by various types of human activities in selected European countries from 2000 to 2006. Data source: The European Topic Centre on Land Use and Spatial Information (ETC/LUSI) LEAC Database (based on the Corine Land cover 2000–06 changes, version 13, 02/2010).9.

Box 2

Major findings on world population and landuse from two recent studies conducted by Goldewijk et al. (2009, 2011)

- From 10 000 BC to AD 2000, the global population increased from 2 to 6145 million people, resulting in a global population density increase of <0.1 capita km^{-2} to almost 46 capita km^{-2}.
- From 10 000 BC to AD 1000, cropland occupied roughly less than 1% of the global ice-free land area, similar to the area used for pasture.
- In the centuries that followed, the share of global cropland and pasture area increased to 2% each in AD 1700 and 11% and 24%, respectively, in AD 2000.

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encroached by humans (Smith and Ward 1998). Floodplain development for human consumption has noticeably downgraded or eradicated their ability to provide ecosystem services and functions: vegetated soils being replaced with impermeable surfaces, riparian forests being replaced by agricultural land, meandering channels being straightened, and so on. Consequences are manifold, for example, reduced infiltration and groundwater recharge, increased overland flow and runoff intensity, shortened travel time, and quickened flood onset (Morris and Wheater 2007). Unfortunately, much floodplain development coincides with development of urban and/or coastal areas. As population growth reduces the likelihood of returning floodplains to their natural states, scientists, engineers, landscape planners, and policy makers face a daunting challenge to find solutions for people to live with floods and reduce vulnerability. Section 5.16.3 Changing Flood Risk and Vulnerability elaborates on flood risk and vulnerability and measures for living with floods and building resilience.

Landuse change is not an isolated factor that acts on its own. Land, as a significant component in the Earth's system, interacts with other subsystems such as the atmosphere, biosphere, oceans, and cryosphere. It modifies the weather and climate through emissions of various greenhouse gases and exchanges of energy, water, and momentum between the land surface and other Earth subsystems (DeFries and Eshleman 2004). Readers can refer to Cotton and Pielke (2007) for a comprehensive exploration and detailed discussion on the climate forcing and feedbacks related to human-induced landuse change at both regional and global scales.

Impacts of climate variability on the water cycle and flooding are better researched than the effects of landuse change. It is perhaps due to the lack of knowledge of how to assess impacts of landuse change in combination with climate, unavailability of past landuse data as baselines, and limited understanding and predictability of human actors' responses to changing flood risk from landuse change. Because of the complex interaction between land and other Earth subsystems, it is vital not to detach impact studies of landuse from those of climate for assessment of future flood risk.

In summary, landuse change is a major human-induced stress factor on the environment. Unprecedented population growth, in parallel with major shifts in global affluence, technological capacity, and socioeconomic organization, is a significant driver of the contemporary landuse change (William and Turner 1992). Consequent changes in the flood characteristics and risks associated with land alteration can result from (1) interaction of landuse change with changes in greenhouse gas emission and radiative forcing that contributes to climate variability and longer-term change and (2) changes of catchment properties including vegetation cover and river channels.

5.16.2 Flood Inundation Dynamics and Impact Modeling

In this section, we are primarily concerned with river or fluvial floods as there has been much recent research into flood inundation dynamics and impacts of environmental change in this area.

5.16.2.1 Flood Inundation Dynamics and Modeling

The physics of floodplain inundation remains a challenge to scientists (Bates et al. 2012). Recently, laboratory experimentation (e.g., Knight and Shiono 1996; Sellin and Willets 1996), field experimentation (e.g., Babaeyan-Koopaei et al. 2002; Nicholas and Mitchell 2003), and remote sensing observations (e.g., Alsdorf et al. 2000, 2007; Bates et al. 2006; Pavelsky and Smith 2008; Schumann et al. 2007,2008a,b) have all resulted in significant advances in understanding of floodplain processes. We now understand much more about turbulent flow around structures during overbank flood flows and the dynamics of shallow plain flooding over complex topography.

The best representation of the physics that is currently conceivable would be to numerically model both river channel and floodplain flows as being fully three dimensional (3D), including turbulence, with solution of the full Navier–Stokes equations. However, for typical flood wave flows, this is prohibitively expensive from a computational point of view. Thus, only those hydraulic processes that are dominant in flood river routing and inundation prediction are currently represented in the most commonly used flood inundation models (Ingham and Ma 2005; Bates et al. 2012). Present understanding suggests that river channel flow may be treated as one dimensional (1D) in the downstream direction but flow on the floodplain when the river goes overbank must be treated as at least a two-dimensional (2D) process (localized zones require 3D representation of turbulent flow), and that flow paths cannot be well predicted a priori (Bates et al. 2012). With 1D model being much of the mainstream, for example, HEC-RAS, there are a number of models representing combined 1D/2D (e.g., TUFLOW, LISFLOOD-FP), 2D (e.g., TELEMAC-2D, SRH-2D), or 3D model (e.g., TELEMAC-3D).

In solving the differential equations of fluid dynamics, several (sometimes subjective) choices need to be made about the discretization of space and time. In terms of spatial discretization, a number of methods are used in computational fluid dynamics, and the three main methods are finite differences, finite elements, and finite volumes. Temporal discretizations are used to find solutions for simulation of unsteady state flows. Readers can refer to Wright (2005) for more details on discretization methods. The selection of discretization in space and time is also dependent on the resolution of available flow data, terrain data, the length scales of terrain features in the domain, and the length and time scales of relevant flow processes. As Bates et al. (2012) note, with the development over the past decade of high-resolution mapping technologies such as airborne scanning laser altimetry, terrain data are usually available at scales much finer than it is computationally possible to model over large areas. However, deciding which terrain and flow length scales need to be incorporated in a model is a much more subjective choice. Clearly, as spatial resolution becomes coarser, particular terrain and flow features will no longer be adequately represented and the impact of these sub-grid scale effects on the model predictions will need to be parameterized (Horritt 2005).

The LISFLOOD-FP model is mainly discussed below as a type of flood inundation model that is capable of capturing 2D complex processes using the raster based approach that is much faster than finite difference or finite element approaches but offers similar level of performance. The LISFLOOD-FP model has been designed to simulate propagation of water over complex topography typically represented by raster data (Bates and De Roo 2000; Hunter et al. 2005; Bates et al. 2010). It is a coupled 1D/2D flood inundation model. The channel flow can be represented using either a 1D kinematic or diffusion wave solved for a rectangular channel cross section using a fully implicit Newton–Raphson scheme. When bank full depth is exceeded, channel flow is transferred to the overlying floodplain raster grid over which flow can evolve in two dimensions. For the 2D floodplain flow, the current version of the model consists of a collection of numerical schemes implemented to solve a variety of mathematical approximations of the 2D shallow water equations of different complexities (ranging from an extremely simple diffusive wave model to a shock capturing Godunov-type scheme based on the Roe Riemann solver, which solves the full shallow water equations). Among these different formulations, the one that was proposed by Bates et al. (2010) has attracted increasing attention for modeling flood propagation over large urban areas. It solves a simplified inertial version of the St. Venant equations, which neglects the convective acceleration term in the momentum conservation equation, yielding a system of two partial differential equations:

$$\frac{\partial h}{\partial t} + \frac{\partial q}{\partial x} = 0 \qquad [1]$$

$$\frac{\partial q}{\partial t} + gh\,\frac{\partial (h+z)}{\partial x} + \frac{gn^2q^2}{h^{7/3}} = 0 \qquad [2]$$

where h is the flow depth [L], t is the time [T], q is the flow per unit width [L^2T^{-1}], x is the distance in the direction of flow [L], g is the acceleration due to gravity [LT^{-2}], z is the bed elevation [L] and n is the Manning's friction coefficient [$L^{-1/3}T$].

The resulting model provides a robust solution to subcritical flood propagation problems over complex topographies at relatively low computational cost.

Recent attempts to represent the processes of importance in flood inundation dynamics with flood inundation models such as the LISFLOOD-FP model have proved successful, even for complex rivers and urban landscapes (Pappenberger et al. 2007; Neal et al. 2011). With the advancement of flood inundation models, a reasonable confidence can be gained in modeled predictions of flood inundation dynamics, although there remain many limitations with respect to data input, process representation and underlying equations, numerical solutions, and computational power.

5.16.2.2 Climate Impact on Floods

It is well understood that climate variability and longer-term change in combination with landuse change would lead to a change in future flood vulnerability (Hulme et al. 2002; Huntington 2006; Wheater, 2006; Frey et al. 2010); however, it is the exact nature of this change in vulnerability that is elusive. This may involve increased economic losses due to damage to infrastructure, property, and agricultural land and indirect losses in or beyond the flooded areas. They can be production losses caused by damaged stock or roads (Linnenluecke et al. 2011), or the interruption of power generation and navigation (Yamba et al. 2011) or just as importantly, the access to renewed livelihoods and homes (social justice) for those flooded, or the sense of well-being and security and changes in risk perception (e.g., Harries 2008). Thus, estimates of flood vulnerability over the next approximately 100 years are essential for planning adaptation and mitigation strategies (Evans et al. 2004). Climate impact on flooding could occur through several pathways: changes in sea level (e.g., a projected sea level rise) could lead to an increased risk of flooding in the coastal areas (Zanuttigh 2011), an increased intensity and frequency of extreme precipitation could lead to an increase in fluvial floods and flash floods, and seasonal precipitation or temperature changes affect snow melt patterns (e.g., Milly et al. 2005; Huntington 2006; Alcamo et al. 2007; Kundzewicz et al. 2005).

There is now a very large body of research that discusses the impact of climate on floods (a few examples being Kay et al. 2006; Bell et al. 2007; Dankers et al. 2007; Graham et al. 2007; Leander et al. 2008). Some of the studies predict an increase in flood frequency, whereas the others report a decrease. This is a reflection of the facts that many hydrological studies focus on individual catchments or small areas, and the complexity of the hydrological phenomena, which means that the 'theoretical expectations' (e.g., more precipitation equals more flooding) are not necessarily supported by empirical evidence to date (Huntington 2006). In addition, it illustrates the inherent uncertainties in climate projections. Therefore, there is an increasing recognition that the uncertainties in climate impact studies need to be rigorously quantified and that a simple estimate of uncertainty is inadequate and could be misleading.

Policy makers need to be presented with reasonable assessment of uncertainties together with cost-loss evaluation as well as vulnerability estimates of taking action or not (Diez et al. 2005). The most popular tools to quantify climate are Global Climate Models (GCMs), but climate modeling is by nature an inherently uncertain activity (Collins et al. 2006). GCMs have had very limited or even no success representing local and regional conditions essential for impact studies (e.g., Semenov 2007; Stephens et al. 2010; Anagnostopoulos et al. 2010). When projections from GCMs are combined with a model cascade (Figure 3) of downscaling models, correction techniques, rainfall-runoff models, and flood inundation models and linked to indicators of vulnerability, the uncertainties involved can be significant and effectively unknowable. It is paramount in impact studies to have a transparent estimate of all uncertainties, which (1) assesses all components contributing to uncertainties, (2) quantifies the combined global uncertainty of the flood vulnerability calculation (the combined uncertainty at the end of the model cascade), (3) acknowledges explicitly the inevitable assumptions that must be made, and (4) quantitatively assess the skill of the models to predict (in a hindcast mode) changes in climate statistics that matter to the floods. It can go some way to dispel skepticism about future climate predictions (Stainforth et al. 2005; Thorpe 2005) and thus future flood vulnerability. It can also enable adaptation decisions to be made more intelligently (Dessai and Hulme 2007). However, there remain scientific challenges in actually achieving a rigorous quantification of uncertainties, because of, for example, complexities in the physical processes, lack of observational data, and constraints in computational time.

Many recent climate impact studies for flood hazard have followed this general framework of a model cascade approach (Cameron et al. 2000; Cameron 2006; Bell et al. 2007; McMillan and Brasington 2008). It is also common in other areas of hydrological science such as flood forecasting (Pappenberger et al. 2005; He et al. 2009). Continuous predictions of meteorological variables (especially rainfall), or stochastic representations of such, are used to drive hydrological and/or hydraulic models to calculate flood inundation extent, water depth, velocity, duration, sediment load, and other variables, which can be transformed to estimates of flood hazard. This type of model cascade approach to assess climate impacts is referred to as the *top-down* (largely adopted by the IPCC investigation and reporting process) or *scenario-led* (Prudhomme et al. 2010) approach. It is a hierarchical approach starting from GCMs driven by future emission scenarios, moving to downscaling and bias correction approaches, and finally cascading to impact models. It is a loosely coupled modeling assembly that can only provide an interim solution to assess impacts of climate on floods and a limited number of snapshots (Jones 2001) of future flood risk projected through time. The uncertainties involved in the model cascade could potentially lead to ineffective flood

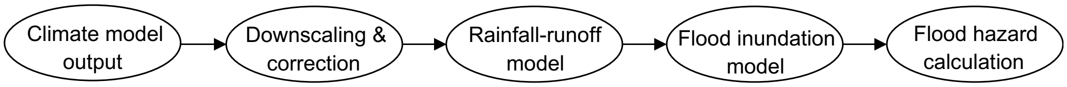


Figure 3 Simple schematic of the linear sequence of a model cascade approach for assessing climate impacts on flood hazard.

management strategies (see discussion in van Pelt and Swart 2011; Blöschl et al. in press). Pielke and Wilby (2012) discuss in more details the limitations associated with this type of approach.

An alternative approach is called the *bottom-up* (Jones 2001) or *scenario-neutral* (Prudhomme et al. 2010). It superimposes every individual flooding impact point resulting from climate model cascades, historical events, recent paleo events, and worst-case sequences of observed weather patterns on a river catchment response surface that covers a plausible collection of changes in response to environmental changes (stresses when their impacts are perceived negative) (Jones 2001; Prudhomme et al. 2010; Wetterhall et al. 2011). The bottom-up impact studies are based on sensitivity analyses of catchment responses to a plausible range of climate (Prudhomme et al. 2010). If all changing factors are considered, a multidimensional catchment response surface is expected to be constructed. The mitigation strategies based on the bottom-up approach may not be optimal from an economical point of view but can be more robust and with *less regret* (Blöschl et al. in press). Readers can refer to Blöschl et al. (in press) for a more detailed comparison between top–down and bottom-up approaches applied in hydrological impact studies.

5.16.2.3 Flood Risk Communication and Visualization

Risk communication is central to international disaster risk reduction strategies (e.g., UN/ISDR 2004; IKSR 2005; IFRC 2009; Pitt 2007), because preparedness and response measures depend not only on the soundness of the underlying scientific risk assessment but also on how effectively the risk information can be conveyed to those responsible for acting on it. Given the potential for scientific error, it is now increasingly recognized that communicating uncertainties associated with probabilistic forecasts is as important for risk management as increasing their accuracy and timeliness (NRC 2006). In the specific context of hydrometeorological climate modeling, formal assessments of uncertainties are thus now a prominent feature of meteorological, hydrometeorological, and climatological research and operational forecasting. While important technical advances have been made in the ability to characterize and quantify hydrometeorological forecast and climate uncertainty, new tools are required to translate this information into clear and effective visualizations that can be easily communicated to decision makers and the general public at large. One example in which such uncertainty is displayed is in operational flood forecasting (Cloke and Pappenberger 2009). Experience in this and other domains suggests that the design and framing of uncertain information is important in shaping how it is understood and acted upon by recipients (NRC 2006). There is also an extensive body of research on how the probability of precipitation forecasts is understood by the general public (Murphy et al. 1980; Gigerenzer et al. 2005; Morss et al. 2008), as well as research on public response to the idea of the 100-year flood (Bell and Tobin 2007) and to the cone of uncertainty visualizations used by the US Hurricane Center to communicate the likelihood of different storm track paths (Broad et al. 2007). Proceeding from an implicit 'deficit model,' much of this work has focused on how the design of risk messages can improve public understanding of scientific uncertainties (Demeritt et al. 2011). However, it is increasingly clear that hydrometeorological climate forecasters (Doswell 2004; Elia and Laprise 2005; Demeritt et al. 2007), like other professional groups (Kostopoulou et al. 2009), are not immune to cognitive and other biases that may distort their understanding of uncertainty and risk. So there are calls for more attention to be paid to the communication of uncertainty of flood vulnerability between different professional groups (i.e., from meteorologists to hydrologists, and from hydrologists to civil protection authorities) involved in flood incident management (Faulkner et al. 2007). There are a number of different ways in which such information could be displayed. Different users are likely to require different kinds of information and thus different visualizations. Expert users may require access to multiple parameters, such as previous observed values, skill scores, and the full uncertainty, all combined in a single information-rich display, whereas other users may prefer simpler displays showing the probability of threshold exceedance and vulnerability. An example of the type of information-rich display is shown in **Figure 4**. Being a simple and quick sketch made in an expert elicitation workshop, it captures the message that this expert user, whose desire possibly represents that of many other expert users, requires not only the corresponding probability of a specific forecast but also the consequence of that particular forecast. It is worth noting here that this information is implicitly based on probabilistic forecasts, not a conventional deterministic forecast. Probability and consequence are the two building blocks for constructing the risk of a forecasted flood event, which will be discussed in Section 5.16.3. Future research will need to put more emphasis on how uncertainties in vulnerability can be displayed and communicated in a more effective way.

5.16.3 Changing Flood Risk and Vulnerability

Flood risk and vulnerability remain at the core of the flood disaster debate. Disaster risk management is discussed by using a variety of terms such as risk, hazard, exposure, vulnerability, coping capacity, resistance, resilience, and adaptive capacity (Merz et al. 2010). On most of these terms, there is no consensus (e.g., Gallopin 2006; Cutter et al. 2008). Against this background, a deliberate attempt is made at defining all terms used in this section of the chapter.

Understanding future flood risk would require a multidisciplinary approach, combining expertise across climate science, catastrophe modeling, economics, and policy (Herweijer et al. 2008). In a nutshell, flood risk and vulnerability in the twenty-first century and beyond will be affected by the following drivers (in order of importance):

1. Population growth
2. Landuse change
3. Urbanization
4. Economic growth in developing countries
5. Rising sea levels.

The alarming reality is that both flood risk and vulnerability are changing for the worse.

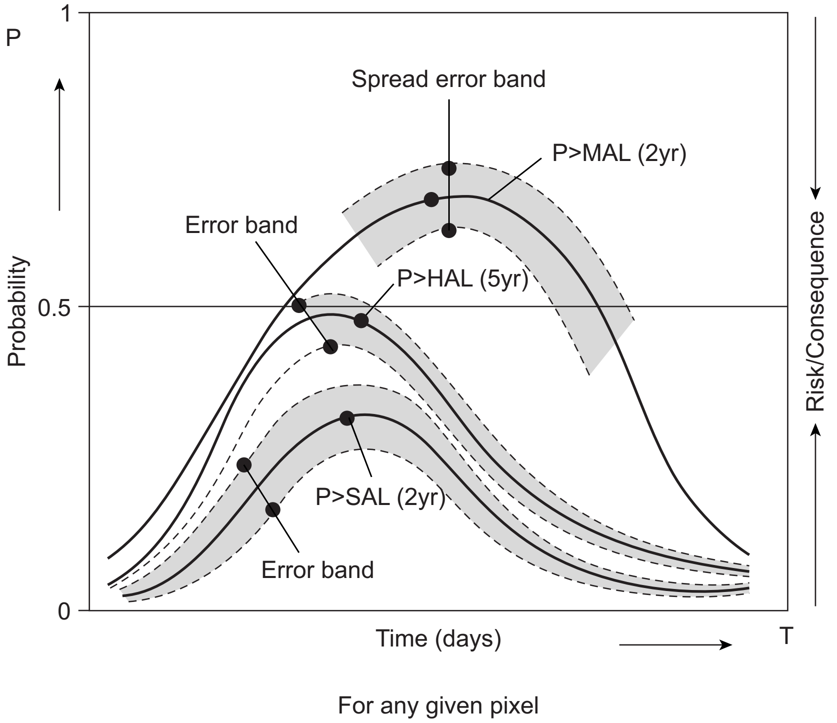


Figure 4 Drawing from an expert election study displaying all components that need to be on a flood forecast across several time scales. From Pappenberger, F., E. Stephens, J. Thielen, P. Salamon, D. Demeritt, S. J. van Andel, F. Wetterhall, L. Alfieri, 2012: Visualising probabilistic flood forecast information: expert preferences and perceptions of best practice in uncertainty communication. *Hydrol. Process.*, doi: 10.1002/hyp.9253.

5.16.3.1 Environmental and Socioeconomic Change

Climate and its related flooding during prehistorical and early historical times have had a profound impact on human settlement and field abandonment, and consequently cultural adaptation (exchange, collapse, or emergence of new culture). Bonsall et al. (2002) provide evidence to demonstrate the correlation between abandonment of the Stone Age sites in the Iron Gates and a distinct global climatic oscillation between *c.*7250 and 7500 cal BP (calibrated years before present), which was a major flood period along the Danube. Farmers were forced to give up riverbank settlements and explore agricultural potential of other areas. The flooding active period was followed by a quiescent period when reduced flood frequency allowed farming settlements to be established on the formally abandoned sites on the floodplains. Cui and Zhou (2003) present a study on the correlation between floods and cultural adaptation in China approximately 4000 years ago when the climate became colder and major flood events persisted for many years. This period is the so-called 'Great Flood of China, which led to population displacement and establishment of a new integrated Chinese culture in the central plain region in China.' The tendency described above continues, and one of the most significant ongoing environmental changes on the planet today pertains to the massive urbanization process taking place in the developing world. Driven by socioeconomic change on a gargantuan scale (probably never seen on the planet), the rapid creation of new hydromegacities (the term hydromegacity refers to major urban areas or metropolises located near or along large water bodies including rivers, lakes, or lagoons) is unstoppable. According to Bonsall et al. (2002), just 25 years ago, less than 2% of the global population resided in 'megacities' of 10 million or more inhabitants. Today, the proportion exceeds 4%, and by 2015, it will top 5%, when megacities will likely house 400 million people (de Sherbinin et al. 2007).

The level of risk in major coastal cities in these countries will grow because of a combination of the five drivers of risk and vulnerability (DRV). In addition, poor infrastructure, immature emergency response apparatus, the presence of slums, and the absence or infantile nature of exposure and vulnerability mapping methods in spatial planning further acerbate the problem. Hanson et al. (2011) show high population and economic exposure to storm surge and flood risk in many of the world's largest and fastest growing cities. Interestingly, Ranger et al. (2011) report that these are also areas where adaptation can have significant benefits. Both flood risk and vulnerability in the future are explored further in the following subsections. Today the proportion exceeds 4% and by 2015 it will top 5%, when megacities will likely house 400 million people (de Sherbinin et al. 2007). Figure 5 illustrates per country population that are estimated to be exposed to coastal flooding in 2007 and 2070. Of the listed 15 countries, 12 can be described as developing nations.

5.16.3.2 What Is 'Flood Risk?'

We define flooding as the subjection of a particular point location, area, or region to unusually high levels of water, leading to temporary or permanent submersion. Risk, in

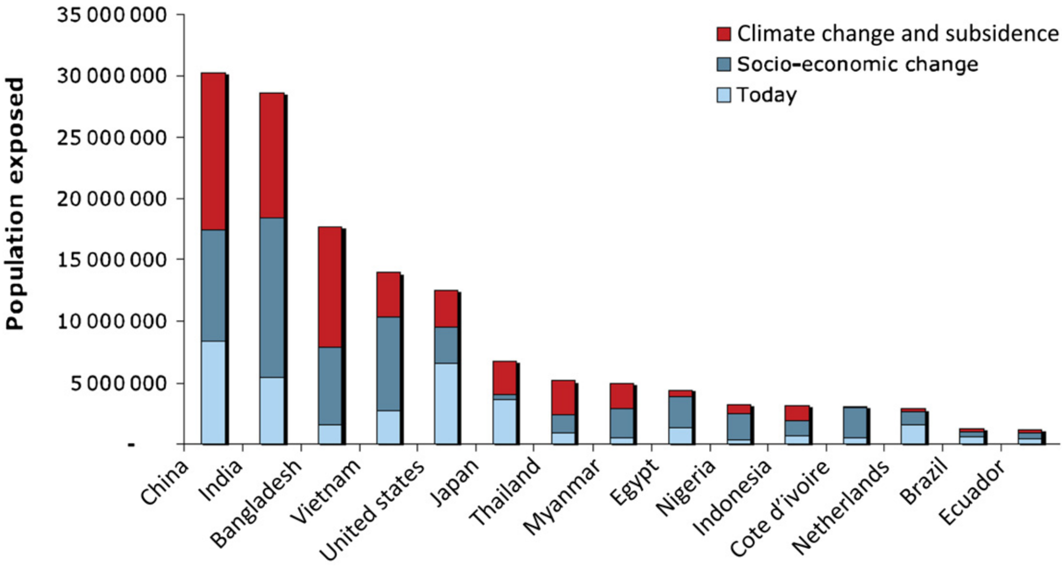


Figure 5 Top 15 countries by population exposed today and in the 2070s, showing the influence of future climate as projected from the IPCC models versus socioeconomic change. Source: Ranking of the world's cities most exposed to coastal flooding today and in the future; OECD press Release, December 2007.

general, can be interpreted as the probability of loss to nature, people, and/or property from a known hazard, as a result of a combination of hazard, exposure, and vulnerability. Flooding can occur anywhere; however, the risk caused by a flood varies in time and space. Variation in time implies that a particular location's propensity to flooding changes with respect to time. For example, flood risk to an art gallery in a city 50 years ago may not be the same today. It might have changed as a result of one or all of the following:

1. Climate variability
2. Landuse change around a nearby retention basin
3. City or urban planning decisions made in the past 50 years

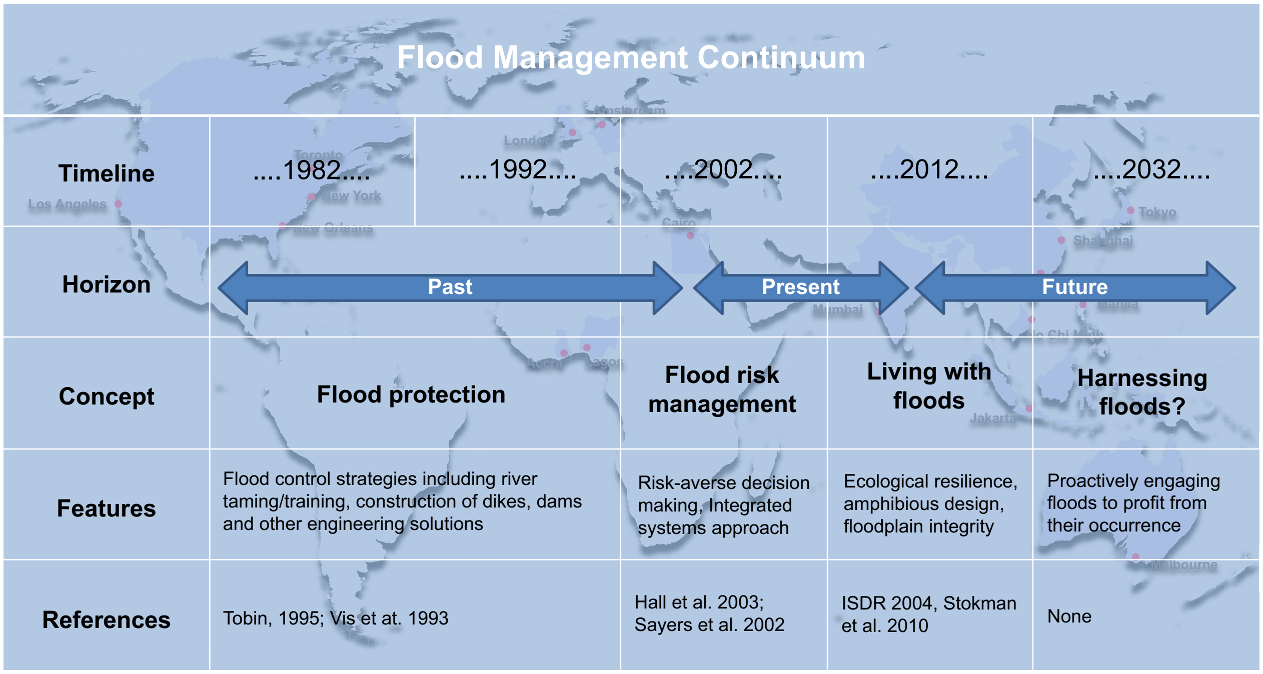
This example practically summarizes the main factors that will affect flood risk and vulnerability in the twenty-first century. Ubiquitous urbanization fueled by population growth and a desire for urban lifestyles, massive landuse change (including record numbers of settlements along coasts, deltas, and estuaries worldwide), and, of course, climate variability will contribute to higher levels of flood risk in the future. These augmented levels of risk will be pronounced in the developing world, where an unprecedented level of population growth and urbanization is currently underway.

There exist several methods to compute flood risk. In this section, we calculate flood risk (F_R) as the probability of flood (F_P) times the consequence of flood (F_C).

$$F_R = F_P \times F_C \qquad [3]$$

Based on eqn [3], one can argue that reducing the flood probability F_P through either engineering interventions (higher dykes or bigger storm drains) or improved forecast lead time can lead to more investment in 'protected' areas, creating a false sense of security and thus increasing the consequences F_C of a potential flood event should 'trusted' defenses fail. The end effect is that although F_P is reduced, should a big flood event breach the reinforced protection, the consequences F_C could be high. In other words, the risk F_R would still be significant (i.e., remain unchanged). This interpretation of eqn [3], which is the norm at present, begs the question: when will our playing catch-up with nature end? For example, if the Q100 (Q100 refers to a 100-year design discharge, that is, a structure designed to handle a flood event that occurs on an average every 100 years) becomes Q50 in 2010 and the Q50 becomes Q5 in 2030, and so on, when does one stop changing his or her design flood, that is, increasing the height of a dyke or the size of a spillway? It is becoming clear that this line of thinking is not sustainable. In other words, given the current knowledge of climate variability and landuse change prognosis, investment in standard human interventions (HI) to *fight* floods might not be the 'smart solution' in the short-term or for the future. We need a paradigm change to concepts that enable us to adapt to new unpredictable flood trends in both space and time. For example, urban design approaches that intelligently accommodate flooding, a concept one might aptly describe as 'living with floods.' We explore this idea in more detail in Section 5.16.3.3 What Is 'Flood Vulnerability?'. **Figure 6**, an evolution of flood management, depicts the change in the perception of flood risk presented as a flood management continuum.

Exploring flood risk would be incomplete without reference to the concept of hazard. According to the *American Planning Association*, a hazard can be defined as "an event or physical condition that has the potential to cause fatalities, injuries, property and infrastructure damage, agricultural loss, harm to the environment, interruption of business, or other types of harm or loss." With reference to the proposed definition of risk, one can surmise that within a specific flood hazard area, there may be similar exposure or risk of flooding but a wide range of vulnerabilities. Most risk quantification approaches follow a standard catastrophe risk modeling framework that combines estimates of hazard, exposure, and vulnerability (Grossi and



Flood Management Continuum

Timeline	....1982....	....1992....	....2002....	....2012....	....2032....
Horizon	Past		Present		Future
Concept	Flood protection		Flood risk management	Living with floods	Harnessing floods?
Features	Flood control strategies including river taming/training, construction of dikes, dams and other engineering solutions		Risk-averse decision making, Integrated systems approach	Ecological resilience, amphibious design, floodplain integrity	Proactively engaging floods to profit from their occurrence
References	Tobin, 1995; Vis et at. 1993		Hall et al. 2003; Sayers et al. 2002	ISDR 2004, Stokman et al. 2010	None

Figure 6 Flood management continuum depicting past, current, and future appreciation of flood management including risk.

Kunreuther 2005). This leads us to the next subsection, which addresses vulnerability.

5.16.3.3 What Is 'Flood Vulnerability?'

We define vulnerability as the ability to resist or recover from the impact of a hazard in both long and short term. An element or a system can be thought of as vulnerable. Buildings or human beings are types of elements, whereas cities, regions, or economies are examples of systems. We represent vulnerability with the following equation:

$$V = f(S, E, R) \qquad [4]$$

where

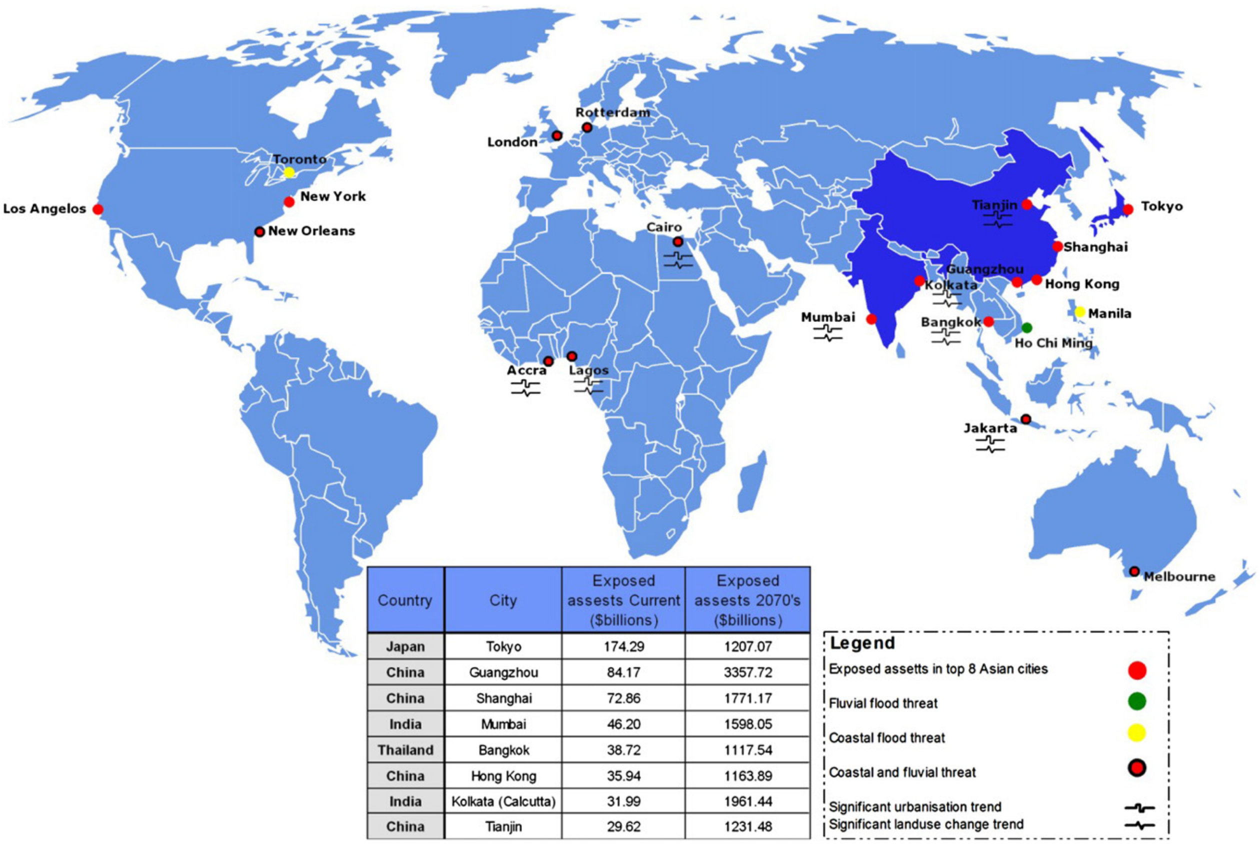
V = vulnerability
S = susceptibility
E = exposure
R = resilience

V depends on many factors including landuse, building design and construction concepts, planning paradigm, forecast skill, effective communication of an impending hazard, and willingness and ability to take responsive actions. Naturally, these factors increase flood risk and also affect vulnerability. Increased unmitigated risk will thus result in high or very high vulnerability, especially under existing paradigms that emphasize increased 'active' HI (higher dikes, better early warning, etc.). Indirect intervention including smart and sustainable urban design or a paradigm shift from 'fighting floods' to 'living with floods' can induce passive resistance to flooding and thus reduce vulnerability. Creating multipurpose infrastructure or waterscapes (Amphibious city landscapes) through amphibious urban design appears to be one of the more promising ways forward, given the current state of affairs.

Both flood risk and vulnerability are important to the insurance and reinsurance industries in which catastrophe modeling is used to determine risk and vulnerability to a range of exposures. Vulnerability, in modeling parlance, can be estimated as the damage cost to a property expected for known water levels expressed in terms of mean damage ratios (monetary damage as a proportion of the total value of an affected property). Benefits of this kind of modeling to an insurer's underwriting strategy cannot be understated. The main output of a probabilistic catastrophe model is the exceedance probability (EP) curve, which illustrates the annual probability of exceeding a certain level of loss (Grossi and TeHennepe 2009). One key risk metric derived from an EP curve is the average annual loss (AAL). AAL is an estimate of the annual premium needed to cover losses from the modeled peril(s) over time, assuming that the exposure remains constant (Grossi and TeHennepe 2009). Figure 7 illustrates global flood vulnerability in coastal and delta cities including the top eight Asian cities in terms of assets exposed to coastal flooding.

5.16.3.4 Resilence—A Paradigm Shift?

Disaster after disaster, we are reminded of the devastating nature of floods. The Mindanao floods on 18 December 2011 in the Philippines claimed over 1100 lives (Agence Presse-France (Philippines floods (December 2011). News item accessed at http://newsinfo.inquirer.net/116107/1000-missing-in-mindanao-floods%E2%80%94government)). The region received a month's worth of rain in just over 3 h. The high death toll was partly because Typhoon Washi hit the southern island in the middle of the night with the worse affected areas being settlements along river banks susceptible to flooding. The storyline is familiar, and, unfortunately, this will not be the last time we



Country	City	Exposed assests Current ($billions)	Exposed assests 2070's ($billions)
Japan	Tokyo	174.29	1207.07
China	Guangzhou	84.17	3357.72
China	Shanghai	72.86	1771.17
India	Mumbai	46.20	1598.05
Thailand	Bangkok	38.72	1117.54
China	Hong Kong	35.94	1163.89
India	Kolkata (Calcutta)	31.99	1961.44
China	Tianjin	29.62	1231.48

Figure 7 Global flood vulnerability and resilience: coastal and delta cities including the top eight Asian cities in terms of assets exposed to coastal flooding. Source: Data from risk management solutions Inc. website, accessed 2011.12.28 at 2000HRS.

hear or read it. The question thus is why this scenario keeps repeating itself the world over. And how can we use current know-how and technology to solve this wicked situation? Naturally, the answer to this question is multifaceted and complicated.

As with most complex issues, it is nearly impossible to have one single solution as an ultimate answer. Resilience is certainly one of the accoutrements in our arsenal in the collective bid to come to grips with the flood menace, worldwide. Building resilience will thus require a multidimensional perspective that combines proven existing methods and novel avant-garde or forward-looking approaches. Resilience is *a state of being* that we can achieve with a set of deliberate steps initiated with a common objective in mind to develop inherent resistance and thus reduce vulnerability to flooding. To attain holistic resilience to flooding, especially in the twenty-first century, we advocate what we term 'living with floods', a form of passive and/or active 'facilitation' of nature's role in minimizing the impacts of floods. Living with floods as a concept per se is not new. However, the version proposed in this chapter goes beyond the conventional view of *living with*, *tolerating*, or *coping with* floods. Figure 8 illustrates the five-element concept composed of two principal components: (1) natural intervention (NI), also known as passive facilitation and (2) HI or active facilitation. 'Living with floods' is a multifaceted approach that inherently engenders resilience.

We define NI as a set of activities that *facilitate* the return of modified or engineered floodplains, estuarine landscapes, and/or river corridors to a state equivalent to conditions before human interference. NI is passive, that is, the motive force behind all objectives is the well-being of 'nature.' The mantra here is ultimate respect and priority for nature in all things flood related. HI, on the other hand, refers to activities initiated or devised by human ingenuity to promote a harmonious human cohabitation with nature. HI is active; in other words, the driving force behind all outcomes of the concept is 'human' or anthropogenic. HI is further divided into the following four elements:

1. HI1: Infrastructure
2. HI2: Amphibious urban design
3. HI3: Water architecture
4. HI4: Awareness

The five-element resilience building concept is discussed in further detail in the following subsections.

5.16.3.5 Natural Intervention

NI is the principal focus of the concept 'living with floods.' Here, landscape restoration especially of floodplains, river corridors, estuaries, and deltas is given priority. Not only do these unique systems have to be restored, they also have to be

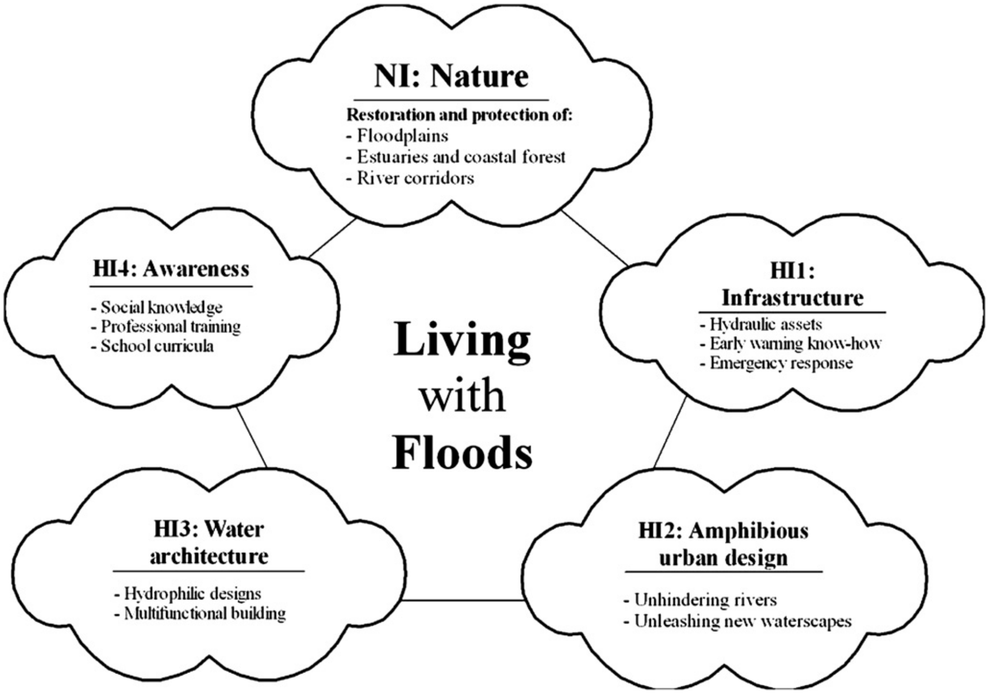

NI: Nature
Restoration and protection of:
- Floodplains
- Estuaries and coastal forest
- River corridors
HI4: Awareness
- Social knowledge
- Professional training
- School curricula
HI1: Infrastructure
- Hydraulic assets
- Early warning know-how
- Emergency response
Living with Floods
HI3: Water architecture
- Hydrophilic designs
- Multifunctional building
HI2: Amphibious urban design
- Unhindering rivers
- Unleashing new waterscapes

Figure 8 Paradigm shift? Living with floods: a holistic perspective toward achieving resilience (NI, natural intervention; HI, human intervention).

protected, by legislation if necessary, to ensure they are able to deliver requisite ecosystem services and functions.

5.16.3.6 Human Intervention (HI)

Human response to the flood menace is as old as the first encounter between humankind and flooding. Building resilience in society would be better served by deliberate attempts at accessing old cultural flood-proofing habitats that have either been lost or ignored by 'modern' thinking. Sultana (2010) makes the distinction between flood control, which generally emphasizes engineering and infrastructural interventions in managing floods, and *flood coping*, which focuses on the indigenous and socially mediated efforts of people to cope with floods and mitigate its impacts. The concept we advocate, especially the HI component, differs significantly from traditional engineering solutions. All infrastructural and engineering endeavors envisaged within HI, conceptually, are intended to complement nature or ensure that floodplains and river corridors return to preimpacted conditions.

The four elements of the HI component of the proposed concept living with floods are intended to cover the entire spectrum of human-mediated resilience. HI1 infrastructure refers to the use of redesigned hydraulic assets to guide or assist floods to achieve their natural function in the landscape. HI2 and HI3, amphibious urban design and water architecture, respectively, follow a similar logic. They expound a rethinking of urban design and planning to reflect the realities of the flood risk mitigation in the twenty-first century and beyond. HI4 awareness, the fourth and final pillar of the four-element HI component advocates creating awareness. Raising consciousness in civil society, especially in highly vulnerable regions of the world, to current intricate sociophysical dynamics that govern floods, prosperity, and the sanctity of nature is the goal of HI4.

From a cursory glance at the situation, one can easily prognosticate a conflict between human development needs and making room for nature, that is, floods. These two objectives are, however, not mutually exclusive. Figure 9(a) shows new Dutch models of using space that would otherwise be unavailable for habitation. Such approaches are not novel as one might think. Figure 9(b) depicts the 400-year-old floating village of Ganvie in Benin, West Africa. Inhabitants of the village a long time ago decided to change their approach to the design and construction of their dwellings to accommodate persistent or permanent flooding witnessed by their forefathers. Is this a form of resilience? Perhaps, in any case, their approach, along with the Dutch 'Paalwoningen' concept, demonstrates the viability of successful coexistence with floods. One could up the ante and suggest the need to develop ideas and concepts that can essentially profit or benefit from the occurrence of floods!

5.16.4 Concluding Remarks

The previous three sections have demonstrated the complexity of a growing flood menace. The competing risks and vulnerabilities stemming from population growth (especially in developing countries), urbanization, landuse change, and climate variability and longer-term change produce a very intricate picture of what effects future flooding might have. The first section makes a clear connection between present trends in environmental change and their potential impacts on floods. Be it urbanization affecting radiative forcing or alteration of catchment characteristics, we know they can only worsen the

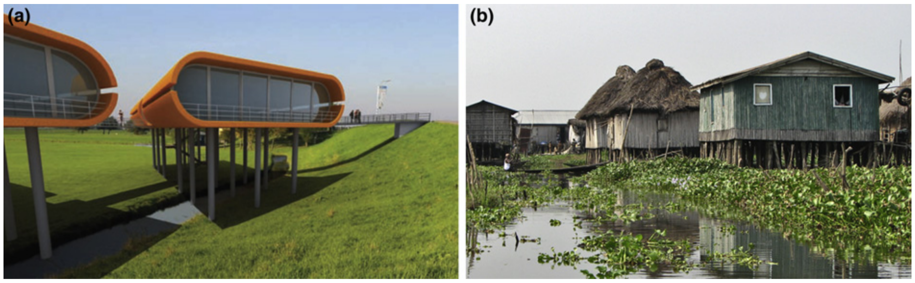


Figure 9 (a) Paalwoningen 'stilt houses,' Haarlemmermeer, the Netherlands. Houses are raised above a floodplain, providing additional living space on an otherwise uninhabitable site. Source, www.waterstudio.nl. (b) The 400-year-old floating village of Ganvie with its famous stilt houses on Lake Nokoué in Benin. Photo copyright: Adrian Shepherd (2008), Department of Biological Sciences, Birkbeck, University of London, UK. E-mail: a.shepherd@mail.cryst.bbk.ac.uk.

impact of floods. The second section dwells on inundation assessment through standard methods such as 2D hydraulic modeling. The lesson here, it appears, is the relative lower levels of uncertainty introduced by inundation modeling as compared to other parts of the flood modeling cascade, in particular, climate prediction. It limits our ability in making reliable statements on the impact of the climate on flood inundation. The fact that future climate input for flood inundation modeling is driven mainly by highly uncertain GCM/RCM output reduces all attempts at forecasting inundation levels in the near and distant future to almost guesswork. The third section assesses the changing nature of flood risk and vulnerability especially in the developing world. It presents the evolution of flood management over the past and proposes the concept of 'harnessing floods' that potentially engenders resilience while advocating working with nature, not against it.

Many of the trends identified in the chapter such as population growth and urbanization, including the creation of megahydrocities, cannot be stopped. To deal with these challenges, it would require ingenuity and new engineering know-how. At the end of the flood management continuum presented in Figure 6, the issue of harnessing the power of floods is mooted. Is this wishful thinking or real engineering goals for the future? Solutions already exist that begin to hint at such thinking. The 'Stormwater Management and Road Tunnel' or 'SMART Tunnel' in Kuala Lumpur (http://www.smarttunnel.com.my/), Malaysia, is an example of multifunctional design that combines storm water control with traffic management. On the forecast front, although there are huge uncertainties in our abilities to characterize and model future floods, progress continues to be made in climate modeling.

The findings in this chapter show that to manage future flood risk sustainably, a portfolio of integrated concepts, measures, and avant-garde thinking would be required.

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5.17 Vulnerability Assessments in the Netherlands Using Climate Scenarios

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5.17.1 Introduction: Climate and Vulnerability in the Netherlands

The Netherlands is a low-lying country in the delta of the Rhine and Meuse rivers, which discharge water from the Alpine and Ardennes highlands in Western Europe toward the North Sea. Throughout the centuries this delta position has created considerable opportunities for socioeconomic development, owing to the sedimentation of fertile land, the use of the rivers for trade and transportation, fresh water availability for agriculture, etc. But the delta environment has also introduced pronounced challenges for the population to adapt to rapidly fluctuating and changing natural conditions, and to protect from hazards such as storms, floods, and droughts.

From the second half of the past century a number of such hazards have strongly shaped the physical and socioeconomic infrastructure of the country. A major flooding from a strong sea surge and storm in 1953 with over 1800 casualties gave rise to the First Delta Programme, which resulted in major coastal defense systems including the sophisticated Oosterschelde and Maeslant barrier constructions. A near flooding of the Rhine River in 1995 and prolonged drought conditions in 1976 and 2003 increased the awareness that also the fresh water supply from the upstream catchment area is subject to strong temporal variability, which needs to be coped with. The Second Delta Committee completed their report in 2008 (Delta Committee 2008), pointing at the need to reconsider the safety levels and design of the defense system both for coastal protection and river management, in order to be prepared for the trends in climate and socioeconomic development that are ongoing and projected.

The awareness of the vulnerable position of the country in a low-lying delta (26% of the Netherlands is below sea level) in general, and the Delta Programmes specifically, have triggered a considerable volume of scientific research in the area of climate variability, hydrological variability, hydraulic engineering, decision support systems, cost–benefit analyses, water use, risk perception, spatial planning, and interactions between all these disciplines and sectors. Since the mid-1990s intensive collaboration exists between Dutch research institutes involved in water management and weather/climate, leading to a suite of projections for impact assessment studies of the Dutch major hydrological systems (e.g., Kwadijk and Rotmans 1995), first-order assessments of climate and possible changes in the frequency of extreme events at the national level (Können 2001), software tools for extreme value statistics (Buishand and Leander 2011), and coupling between meteorological and hydrological/wave models (FEWS 2011). More comprehensive research programs were developed in the early 2000s, in particular the Dutch National Program on Global Air Pollution and Climate Change (NRP; Berdowski et al. 2011), Climate Changes Spatial Planning program (CCSP 2011) (2004–11), and the Knowledge for Climate program (KfC 2011) (2007–13). CCSP was designed as a multidisciplinary research program focusing on the development of climate scenarios, land use-related mitigation options, sector-specific adaptation projects, and cross-cutting cost–benefit analysis and spatial planning projects. It paved the way for further analysis of climate adaptation options for a number of vulnerable 'hotspots' in the Netherlands, including the Rotterdam harbor, Schiphol airport, the rural peatland and sand areas, and the coastal/river defense systems in KfC. In addition, the Second Delta Committee report focused on a limited number of vulnerable hotspot areas where either the chance for occurrence of extreme disrupting events or the socioeconomic consequences of such events were contributing to a high risk level. Research supporting this influential Delta Committee report relied heavily on the lively multidisciplinary research networks that were created by the CCSP and KfC programs.

Traditionally, the systems for water management and other infrastructure have been designed under the assumption that climate is stationary (Klein Tank et al. 2009). New infrastructure is typically designed on the basis of historical information on weather and climate extremes, where the maximum value of a particular variable in the historical record is considered to be the normative value for design. In other cases, extreme value theory has been applied to the historical observations of extremes to estimate the normative value, again disregarding

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changes in the climate statistics. The notion of the mean, variability, and extremes of relevant weather variables is now widely accepted. Recent adaptation strategies begin to account for the changes in extremes observed in the past decades, as well as projections of future changes in extremes such as are obtained from climate models. Some types of infrastructure currently have little margin to buffer the impacts of changes in climate statistics. A recent evaluation (Ten Brinke et al. 2008) indicates that at least 15% of the primary dike system in the Netherlands does not meet the safety standards as set down in Dutch national law because of increasing sea height extremes associated with rising sea levels. In other cases, projected changes (although highly uncertain) are so large that simply relying on traditional adaptation methods would no longer appear to be prudent.

To guide this process, the Royal Netherlands Meteorological Institute (KNMI) developed a set of climate change scenarios, containing indicators of changes in the mean and extremes of a number of relevant climate variables, relative to a reference period (KNMI'06, Van den Hurk et al. 2007). In this chapter, the terminology 'climate change' refers to changes in climate statistics over multidecadal time scales. Although the construction of KNMI'06 follows a typical top–down information chain approach (from the Intergovernmental Panel on Climate Change (IPCC) Special Report on Emissions Scenarios (SRES) to a range of climate projections to a set of downscaling steps to a statistical post-processing at the local level using observations to a variety of sector-specific impact assessment tools, leading possibly to an appropriate response), the scenarios have been designed to serve as a benchmark for bottom–up application in different sectors in which vulnerable hotspots are taken as a starting point with the eventual goal to derive adaptation strategies. This bottom–up procedure (also addressed as 'adaptation tipping point analysis'; Kwadijk et al. 2010) essentially follows a reversed chain of analysis: after defining potential impacts that need to be avoided or mitigated, an assessment of the corresponding climate characteristics that lead to these impacts is made. Comparison with climate projections is applied to determine whether/when these conditions can be expected.

This chapter discusses a number of recent Dutch case studies against the background of the seven key guideline questions corresponding to a vulnerability-based assessment (Wilby and Dessai 2010; Pielke et al., in press). In these case studies, both climate and socioeconomic drivers play a role. In each of these case studies the vulnerability aspects will be reviewed, the impact of climate on these aspects will be assessed, and a discussion of the communication of climate change information by means of a discrete set of scenarios will be included. After these (bottom–up defined) case studies, a brief description of the construction and rationale behind the (top–down oriented) KNMI'06 scenarios will be described. Particularly, the confluence of the top–down and bottom–up approaches is illustrated by examining the role of the scenarios as a benchmark in these and other vulnerability assessment studies, and the stakeholder involvement in their design and update. The chapter concludes with a general assessment of the degree to which the climate change scenarios have been helpful for adaptation in the Netherlands.

5.17.2 Case Studies in the Context of Vulnerability Assessment

According to Pielke et al. (in press), a bottom–up analysis of vulnerable resources should be built around seven key questions:

1. Why is this resource important? How is it used? To which stakeholders is it valuable?
2. What are the key environmental and social variables that influence this resource?
3. What is the sensitivity of this resource to changes in each of these key variables? (This may include, but is not limited to, the sensitivity of the resource to climate variations and change on short (days), medium (seasons), and long (multidecadal) time scales).
4. What changes (thresholds) in these key variables would have to occur to result in a negative (or positive) outcome for this resource?
5. What are the best estimates of the probabilities for these changes to occur? What tools are available to quantify the effect of these changes? Can these estimates be skillfully predicted?
6. What actions (adaptation/mitigation) can be undertaken in order to minimize or eliminate the negative consequences of these changes (or to optimize a positive response)?
7. What are the specific recommendations for policy makers and other stakeholders?

To provide a motivation for each of the case studies (described in more detail in the following subsections), these questions have been addressed briefly as summarized in **Table 1**.

The first case study (Te Linde et al. 2011) describes a climate and socioeconomic scenario assessment for the Rhine area. The flood-prone areas near the riverbanks are protected by a mixed set of safety measures for a given design river discharge. For this particular area, the stakeholder population is quite broad: in fact, all socioeconomic factors in the flood-prone area are to be considered. Apart from changes in climate-related discharge regimes, increasing concentrations of socioeconomic value in the riparian areas are changing drivers, leading to a necessary reassessment of the current design discharge. This design discharge can be changed by infrastructural measures, in combination with exploration of revisiting disaster policies, financial arrangements, and liability structures, such as recommended by the Second Delta Committee.

A second case study describes the coastal defense strategy analyzed in detail by the Second Delta Committee. As for the Rhine area, a storm surge defense infrastructure is constructed based on rare extreme surge levels with a predefined (design) return time. This case study also assigns a wide range of stakeholders, owing to the high socioeconomic value located in the Dutch coastal area. Critical drivers and thresholds are determined by both climatological sea level and associated storm surge regimes, and socioeconomic pressure on the area. An expert evaluation of possible sea level change during the twenty-first century has resulted in a range of values, of which the upper value is of higher relevance than the low end of the range, because of the asymmetric socioeconomic implications. Migration of the population away from the area below sea level is far less feasible than adopting sophisticated flood protection

Table 1 Overview of key questions of vulnerability assessment for the case studies

		Case studies		
No	*Question*	*Rhine discharge*	*Coastal defense*	*Extreme precipitation*
1	Why/for whom is resource important?	Everybody. Densely populated area, large socioeconomic value	Everybody. Densely populated area, large socioeconomic value	Urban water management. Regional water management. Emphasis on coastal areas
2	Key environmental and socioeconomic variables	High discharge. High concentration of socioeconomic value along river banks	Extreme storm surge. High concentration of socioeconomic value along coast	Extreme precipitation. Land use
3	Sensitivity of resource to change in key variable	Increases in high discharge and socioeconomic value both increase risk for damage	Increases in storm surge risk and socioeconomic value both increase risk for damage	Higher extremes and more intense land use (urbanization) lead to more damage
4	Thresholds leading to positive/negative response	Present norm: 16 000 $m^3\ s^{-1}$, based on somewhat arbitrary assessment of ‘acceptable risk for damage’	Present norm: 1/10 000 years, based on somewhat arbitrary assessment of ‘acceptable risk’ (a 1% chance for a major flooding per century)	Urban areas: sewage design should withstand 1/10 years showers. Polder areas should flood less often than once per year
5	Best estimates of probabilities of thresholds to occur	For both drivers: dependent on chosen scenario. Scenarios reflect uncertainty in future developments	Storm surge: expert judgment says 60–120 cm by 2100. Only upper value of this range is ‘politically relevant’	Inland showers: intensity scales with temperature change. Coastal heavy rain: change of North Sea temperature is a driver. Land use: urbanization will increase
6	What adapation/mitigation actions?	Flood protection measures. Increasing design discharge	Stronger coastal defense. Moving away socioeconomic value from coastal area is for the time being not an option	Bigger sewage systems/pumping systems. Water retention integrated in landscape
7	Recommendations for policy makers	Follow Delta Committee recommendations	Follow Delta Committee recommendations and apply adaptive management (monitoring actual sea level rise)	Increase resilience by technology

as an adaptation measure. The Delta Committee recommended applying 'adaptive management' here and keeping the coastal defense system in line with updated information on sea level rise (SLR) and socioeconomic developments.

A final case study is included here to illustrate the role of climate change scenarios as a picture of possible future conditions, rather than as predictive tools. The summer of 2006 was characterized by a very hot July followed by a very wet August, leading to severe flooding in some urban areas near the North Sea coast. These extreme precipitation aspects also have a mixed set of stakeholders. Waterboards are responsible for water management in the rural and urban areas, but response measures in the rural area (pumping capacity, (ground) water management) differ from infrastructural measures (sewage design) in the urban areas. Climatic drivers behind changes in extreme precipitation levels vary across the country, where the North Sea exerts a clear influence on the coastal area. Increasing resilience by technological measures is one of the most straightforward adaptation measures.

5.17.3 Protection against River Floods in the Rhine Basin

The Rhine is a mixed rainfall/snowmelt river with a mean discharge regime that shows a relatively small annual cycle with a maximum in late spring and a multiyear mean of approximately 2300 $m^3\ s^{-1}$. Flooding events are governed by multiday episodes of widespread rainfall across the 160 000-km^2 large basin, excessive snow melt from Germany and the Alpine area in response to high temperatures in spring, or a combination of these (Te Linde et al. 2011). Estimates of the 1/1250-year return level based on extreme value statistics using historic discharge records result in a value of 16 000 $m^3\ s^{-1}$ as the current design discharge for the majority of river bank areas in the Netherlands.

The Rhine Delta is a densely populated area. Over the past century the historic discharge time series has been affected by upstream infrastructure measures (dikes, straightening stretches for shipping, retention areas) and water management (e.g., lake level control in Switzerland). Urbanization and concentration of capital in major industry areas has increased the economic and societal value of the area along the river that is prone to flooding (Klijn et al. 2004). The ongoing concentration of socioeconomic value along the riverbanks together with changes in the discharge regime induced by climate and infrastructural developments has increased the need to reassess the acceptable flood risk, as noted by the Second Delta Committee.

Many studies have been conducted addressing the implications of changing climate statistics for the extreme discharge regime of the Rhine. These were pioneered by the study of Kwadijk and Rotmans (1995), who showed that the seasonality of the mean discharge regime shifts from a mixed rain/snowmelt river toward a rainfall-dominated system under warming conditions. Increases in projected winter precipitation leads to increases in the design discharge, and multiple studies using different approaches have confirmed this increase, with a range of design discharge increases between roughly 1000 and 3000 $m^3\,s^{-1}$ for the year 2100 (Shabalova and van Deursen 2003; Lenderink et al. 2007b; Ward et al. in press).

However, the vulnerability of the riparian area is affected not only by changes in the climate-driven peak discharge but also by the potential damage caused by a flooding event. In the context of the Delta Committee assessment and the CCSP research program, Te Linde et al. (2011) and Ward et al. (in press) explicitly included this nonclimatic aspect of vulnerability changes in their studies of anticipated changes in the flood risk for the Rhine area.

Te Linde et al. (2011) analyzed the present and future flood risks for a number of areal stretches along the main branch of the Rhine River (**Figure 1(a)**). Flood risk is here the product of the annual probability of flooding in a given area and the expected damage when flooding occurs. The estimates are based on a modeling chain involving historic climate data (precipitation and temperature), hydrological processes, hydraulic flooding, and an economic loss model driven by inundation depths. For a limited number of climate scenarios, protection measures, and land-use scenarios up to 2030, changes in this flood risk are calculated. The land-use scenarios are socioeconomic translations of the regional distribution of economical value in the riparian areas in response to large-scale socioeconomic drivers, leading to an increase in the property value in the area of interest. The two climate change scenarios used in this study were constructed from very different approaches, but both led to a substantial change in the precipitation regime relevant for flood occurrence. This approach is not intended to cover a specific uncertainty range in future climate conditions, but merely illustrates the sensitivity of flood risk to changing climate statistics over a hypothetical range of conditions. In total, six scenario calculations were conducted: two climate change scenarios, two land-use scenarios, and two situations where both were applied (combining a smaller or larger climate change signal with a smaller or larger land-use change projection, respectively). In this set-up the flood risk increased in all scenarios, and the climate signal dominated the land-use signal (**Figure 1(b)**). However, the simulations with both high-end scenarios combined resulted in a larger increase in the flood risk than the summation of the two separate climate/land-use scenarios. Thus, the damage due to the change of one acting agent depends on the change of the other acting agent. A straightforward interpretation of this finding is that for a stronger increase in the socioeconomic value in a flooded area the risk effect for a given event is larger.

A later study by Ward et al. (in press) elaborates on this using a probabilistic framework. In their approach, a similar modeling chain was set up, but a larger sample of climate change scenarios was processed, derived from downscaled data sets from 12 Global Climate Models (GCMs) used for the fourth IPCC assessment report (AR4) (Van Pelt et al. submitted). Apart from a general confirmation of the findings of Te Linde et al. (2011) this study illustrated the use of a wide sample of scenario projections to compute the probability for a given damage to occur. Acknowledging methodological limitations they used their probabilistic sample and estimated the probability of the high flood damage scenario shown by Te Linde et al. (2011) to be between <0.1 and 11%, depending on the specific target area.

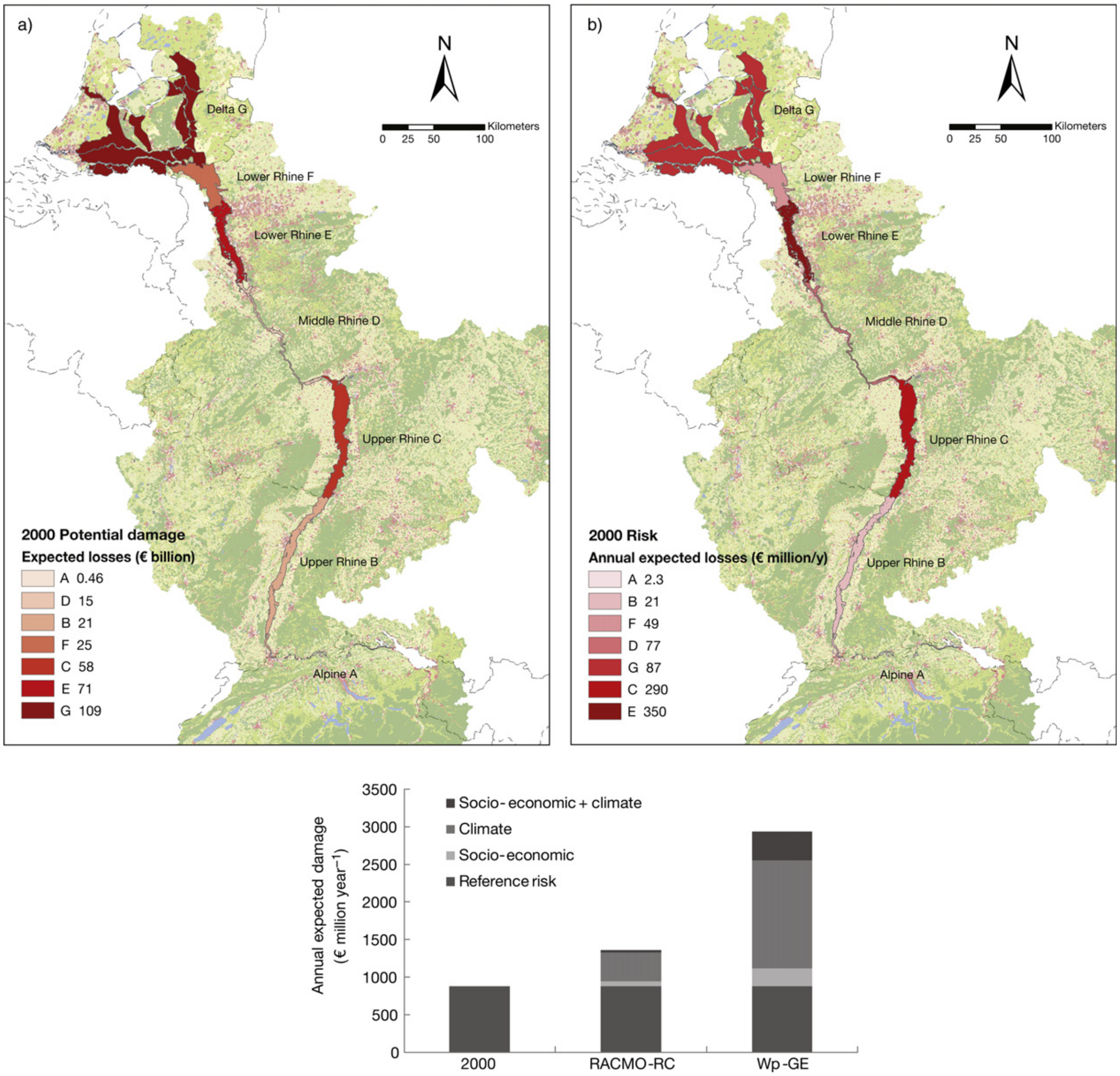
a)
N
Kilometers
0 25 50 100
Delta G
Lower Rhine F
Lower Rhine E
Middle Rhine D
Upper Rhine C
Upper Rhine B
Alpine A
2000 Potential damage
Expected losses (€ billion)
A 0.46
D 15
B 21
F 25
C 58
E 71
G 109
b)
N
Kilometers
0 25 50 100
Delta G
Lower Rhine F
Lower Rhine E
Middle Rhine D
Upper Rhine C
Upper Rhine B
Alpine A
2000 Risk
Annual expected losses (€ million/y)
A 2.3
B 21
F 49
D 77
G 87
C 290
E 350
Annual expected damage (€ million year⁻¹)
3500
3000
2500
2000
1500
1000
500
0
Socio-economic + climate
Climate
Socio-economic
Reference risk
2000
RACMO-RC
Wp-GE

Figure 1 Summary of the analysis of Te Linde, A. H., P. Bubeck, J. E. C. Dekkers, H. de Moel, and J. C. J. H. Aerts, 2011: Future flood risk estimates along the river Rhine. *Nat. Hazards Earth Syst. Sci.*, **11**, 459–473, http://dx.doi.org/10.5194/nhess-11-459-2011. (a) Current (reference year 2000) flood risk expressed in million euros per year for a number of riparian areas along the main Rhine branch. (b) Total risk in the investigated areas for the reference year and for 2030 for two climate and socioeconomic scenarios. The low/high climate change scenarios The label "RACMO" represents a low scenario, while "Wp" represent a high scenario are combined with the low/high land-use change scenarios (low: RC; high: GE), respectively (see text).

Both studies stress the limited scope of their analyses, and present their results for illustration and methodological demonstration purposes only. Here it needs to be emphasized that the quantitative results of these studies are not to be considered as a representative estimate of scenario-specific future conditions for the flood damage in the Rhine area. However, the studies do illustrate clearly that a nonlinear response of socioeconomic developments and climate exists at the regional spatial scale at which vulnerability assessments normally are applied. They do demonstrate the need to incorporate nonclimatic scenarios or other forms of uncertainty mapping (Bubeck et al. 2011), and call for a continued and reinforced cooperation between the relevant disciplines involved.

5.17.4 Coastal Defense: Storm Surges and Sea Level Rise

As discussed earlier, the Netherlands is subject to large fluctuations in the physical environment. Historically, frequent floods not only shaped the country but also gave rise to the design of a robust flood defense system, both from coastal and riverine directions. The coastal defense and water sectors were early adapters to climate.

The first major Delta Programme, completed a decade ago, is designed to reduce the probability of occurrence of events similar to the Zeeland flooding in 1953 to once per 10 000 years in regions of high economic value, down to once

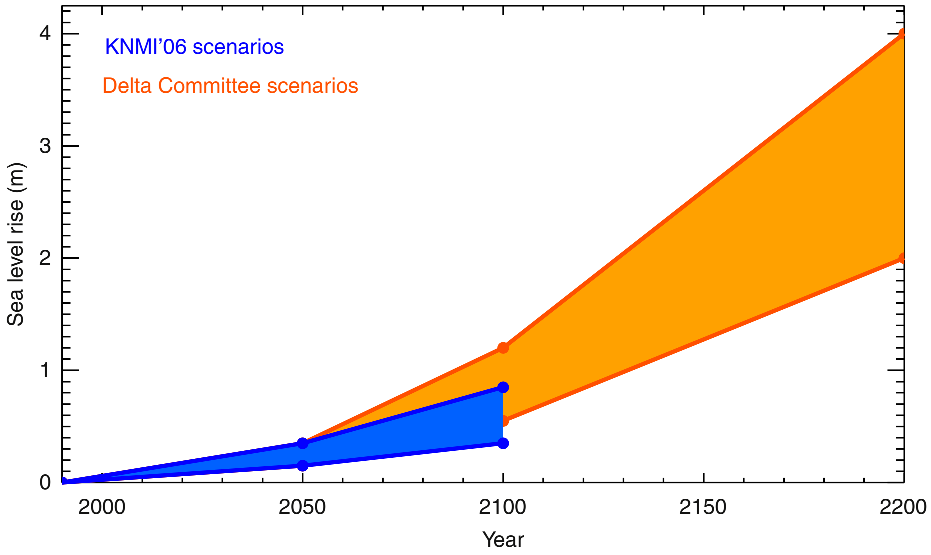

Figure 2 Scenarios of sea level rise from KNMI'06 (blue) and from the Delta Committee (orange). Vellinga, P., C. A. Katsman, A. Sterl, and J. J. Beersma, Eds., 23/11/2009: *Exploring high-end climate change scenarios for flood protection of the Netherlands. International Scientific Assessment carried out at the request of the Delta Committee*. KNMI publication: WR-2009-05, [Available online at http://www.knmi.nl/bibliotheek/knmipubWR/WR2009-05.pdf]

per 1250 years elsewhere. This return level, the so-called safety standard, is not objectively based on economic cost/loss calculations, but reflects the major society concern of exposure to such devastating events. Changes in climate statistics, or the related SLR, was not considered in this First Delta Programme: the calculations of the water levels with a return time of 10 000 years used to design coastal and riverine defense structures were based on statistical extrapolation of observed and modeled sea level fluctuations of the past, assuming a stationary mean climate.

Since the second half of the twentieth century, the situation has changed. Changes in climate statistics are now an issue of concern in this low-lying delta. In addition, increased value of the society capital protected by the flood defense systems has given rise to reconsider the 1/10 000 years safety standard. The Second Delta Committee (2008) resulted in a scientific reassessment of the Dutch coastal defense system. This reassessment comprised both an evaluation of SLR and updated modeling capacity for storm surge projections (Sterl et al. 2009; Van den Brink et al. 2004). Here, the evaluation of SLR has been discussed in detail.

The KNMI'06 climate change scenarios include estimates of the projected mean SLR at the Dutch coast for different global mean temperature scenarios, leading to values between +35 and +85 cm in 2100 relative to 1990. Following AR4, the Second Delta Committee realized that sea level scenarios are subject to considerable uncertainty, including the role of major ice sheets, global mean temperature rise, paleoreconstructions on rates of global mean sea level change, and previously underrepresented mechanisms such as gravitational effects of ice sheet changes and ground water extraction. As a result, the range of SLR that should be taken into account for coastal defense may be much wider than represented by KNMI'06. A semiobjective procedure was followed by asking an international team of experts to provide a consensus assessment of the plausible high-end sea level change in 2100 and beyond, incorporating the multiple uncertainties associated with this estimate. This committee (Vellinga et al. 2009; Katsman et al. 2011) provided a range of high-end sea level changes between +55 and +120 cm (excluding effects of local surface subsidence), which is different from reporting on the full range of possible SLR scenarios (Figure 2). This difference in assignment explains the difference in the sea level scenario values relative to KNMI'06.

The Delta Committee emphasized the gradual evolution of SLR over time and recommended an adaptive approach, updating measures frequently considering the actual SLR taking place. In all written communications about these sea level scenarios the full range of this assessment (+55 to +120 cm) is used. However, in some political debates in and around the Dutch Parliament, and in some newspaper releases, the Delta Committee tended to emphasize the high end of this scenario range (+120 cm), without giving adequate credit to the reported range of scenarios as perceived by the team of experts. It clearly reflects the differences between scientific and political perspectives of this uncertainty range. The scientific desire to communicate an objective (wide) uncertainty range is not always compatible with the political need to create a sense of urgency.

5.17.5 Extreme Precipitation in the Coastal Area

A high-impact quantity is the occurrence of extreme precipitation, both at the local scale (heavy showers leading to sewage problems, flash floods, construction damage) and at a more widespread regional scale (affecting peak discharge of major rivers or water management problems in watersheds). But the events of extreme precipitation in Western Europe are very episodic and erratic, with low predictability, low consistency, and weak links to nearby or remote drivers.

The concept of climate scenarios is frequently challenged by historic sequences of weather episodes, including the occurrence of extreme precipitation. The summer scenarios of KNMI'06 discern between a relatively dry climate in response to an increase in prevailing easterly winds (with lower wet day frequency and small increases of extreme precipitation) and a warming response without changes in the prevailing wind directions, which is associated with a low change in the wet day frequency but a strong increase in the extreme precipitation level (here defined as the 1/10 year wettest day). Summer 2006 in the Netherlands is remembered by a warm, sunny, and dry July, followed by a very wet August, particularly in the coastal areas that were affected by the high North Sea surface temperature following the warm July episode (Lenderink et al. 2008). One could associate July 2006 with the dry/warm scenario, and August 2006 by the wet/warm scenario. This interpretation violates the nature of scenarios as being illustrative for multiyear climate conditions in which dry and wet episodes both do occur but with different frequencies, yet it also provides a recognizable iconic image for these particular scenarios. In addition, it illustrates the fact that true weather does not follow human-defined scenario pathways, but essentially consists of a superposition of considerable natural variability upon a relatively small change in the mean state. Lenderink et al. (2009) reported on this Summer 2006 event by analyzing the impact of the anomalously high North Sea temperature on the coastal precipitation, providing useful guidance of the KNMI'06 climate change scenarios.

5.17.6 Climate Change Assessments in the Netherlands

The KNMI'06 climate change scenarios (Box 1) allowed a range of society sectors to assess the implications of possible changes in the local climate statistics for their particular applications. For many stakeholders the notion of 'climate change' is related to the time scales that are relevant to a particular application. For example, for the engineers involved in the design of sewer systems with a typical life span of 50 years, changes in climate statistics used for their design criteria (often the historical 50-year period) are referred to as 'climate change.'

The four scenarios emphasize the location of the Dutch delta in a transition zone: in Northern Europe a pronounced increase in wintertime precipitation is projected, whereas the decrease in summertime precipitation is a prominent feature in most future climate projections in Southern Europe. Aspects of both features appear in the four scenarios for the Netherlands. The uncertainty in the signature of this change in the transition zone is also reflected in the strong interannual variability of contemporary seasonal precipitation and temperature in the Netherlands, highly depending on predominant atmospheric circulation conditions.

The KNMI'06 Climate Change Scenarios and Their Updates

The KNMI'06 climate change scenarios for the Netherlands (Van den Hurk et al. 2007) replaced the older Können (2001) scenarios. KNMI'06 was based on an integrated assessment of state-of-the-art climate projections from Global Climate Model (GCM) simulations prepared for the fourth IPCC assessment report (AR4), downscaled data from a suite of Regional Climate Model runs (RCMs; Jacob et al. 2007) and local observations, and regionalization of the IPCC sea level scenarios (Katsman et al. 2010). The ultimate product of KNMI'06 consisted of four descriptive pictures of future climate in the Netherlands expressed as sets of change factors for a number of relevant seasonal meteorological variables (temperature, precipitation, potential evaporation, and wind) for different statistical moments (allowing changes in the mean to be different from changes in extremes). The four sets (or scenarios) were designed to span a fair amount (roughly 80%) of model-based uncertainty in global temperature change and the regional expression of that global change (Lenderink et al. 2007a).

Preparations for a next set of climate change scenarios are currently underway (with the working title 'KNMInext'), driven by a mix of new or updated stakeholder requests (see main text) and progress in the scientific insights and available tools. KNMInext will further develop the concept of 'Future Weather' (Hazeleger et al. submitted), where high-resolution, high-quality, specifically targeted simulations will be used as a virtual laboratory for future weather, with all its spatial and temporal modes of variability that are relevant for the application at hand. The case study of the Dutch North Sea in Summer 2006 is an illustrative example of such a targeted simulation. Simultaneously, tools are being developed to analyze observed anomalous episodes in the context of changes in climate statistics (Stott et al. 2011). The call for this attribution becomes louder: are these events an expression of systematic changes in the frequency of different weather patterns and can we expect more of this to come, or is natural variability the main cause and can current adaptation policy be considered adequate?

KNMI'06 served a wide range of sectors vulnerable to summer droughts (rainfed agriculture, nature conservation, cooling demands for power plants, and soil salinification in the coastal area), seasonal floods (coastal and river defense systems, sewage design in urban areas, and land accessibility for agricultural management), and wind/storm climate (coastal defense, wind energy, and air traffic). For each of these sectors, pilot studies or hotspot analyses were driven with KNMI'06 scenarios as boundary condition, and different (or sometimes additional) scenarios were chosen by different sectors because of a variety in climate regimes to which vulnerability exists (see the coastal defense case study for an example). The climate variables included in the KNMI'06 scenarios were also chosen in close cooperation with stakeholders in the vulnerable sectors: high discharge levels in the Rhine are driven by multiday precipitation extremes, while single-day or even single-event precipitation extremes are boundary conditions for sewage design in urban areas and water table management at polder level. KNMI'06 got a legal status in the National Water Plan (NWP 2011), where timing and target safety levels of maintenance and new developments of the national and regional water systems are regulated between the national and local governments. In addition, the Second Delta Committee assessment and many other sector-specific applications use KNMI'06 as a reference. The development of the scenarios and the incorporation of state-of-the-art model projections have received attention from among others Belgium (that contracted KNMI to produce a similar set of scenarios for their territory), and resembles aspects of the approach followed in other countries such as Australia (CSIRO 2007; Whetton et al. 2012) and Switzerland (OCCC 2007).

The extensive use of KNMI'06 also revealed some shortcomings, many of which have been communicated by users of the scenarios. For instance, it does not contain spatially explicit climate change information. This is unrealistic when considering the considerable climatological gradient across the large Rhine Basin (where changes in the Alpine snow regime will have a different seasonal signature than the projected rainfall changes in the lower parts of the basin). However, at a smaller spatial scale a gradient in the changes in climate statistics is evident. Coastal areas are exposed to considerably higher rainfall rates during warm North Sea conditions in late summer (see earlier).

Another add-on request to KNMI'06 was the exploration of subdaily precipitation extremes, which is a high-impact quantity (leading to sewage problems, flash floods, and construction damage). In particular, the urban environment is very sensitive to short-duration precipitation extremes. Analyzing a large data set of observed hourly precipitation both in De Bilt and in Hong Kong, Lenderink and Van Meijgaard (2008) concluded that the dependence of rare heavy precipitation events on surface dew-point temperature turned out to be much stronger than generally obtained in regional (and global) climate model simulations (Figure 3). Other examples of 'relevant scientific progress' since the release of KNMI'06 exist (such as the analysis of observed temperature trends over western Europe by van Oldenborgh et al. (2009) and the contribution of changes in the gravitational balance by ice sheets to regional SLR by Katsman et al. (2011)). An update of KNMI'06 was published in 2009 (KNMI 2009), where additional guidance to the interpretation of the scenarios was given without a significant alteration of the scenario values themselves.

The Second Delta Programme, launched after the recent advice from the Delta Committee, has generated a set of 'Delta scenarios,' of which changing climate statistics is one of the drivers. Major additional inputs are provided from anticipated changes in land use and socioeconomic key factors such as agriculture, urbanization, economic growth, and property values (Bruggeman et al. 2011). An essential component of these scenarios is a consistent storyline, in which society and environmental developments are pictured in a common framework. In storylines in which economic growth is anticipated to be large, adverse climate effects can be mitigated more easily than for low economic growth rates. Vice versa, the economic growth rate in the Netherlands is a projection of the global economy, and thus the association between economic growth and greenhouse gas emissions (and a climate response to this) should be considered.

These and other developments illustrate the dynamic scientific and policy arena in which climate information is used, updated, and refined.

5.17.7 Concluding Remarks

An important and ongoing discussion addresses the basic intended objective and relevance of (climate change) scenarios (Pielke et al. in press; Wilby and Dessai 2010). One may consider the ensemble of scenarios as a subset of uncertainty in future climate conditions, and the ensemble should be preferably constructed in a way such that a wide range of sources of uncertainties is covered, which are meaningful to the application considered. Alternatively, one may hypothesize that every scenario is a (relevant) case study that is consistent with a given direction of future (climate/socioeconomic) developments, and is adequate for testing a planned adaptation measure under realistic conditions. KNMI'06 scenarios allow both forms of application. For instance, in the context of the Second Delta Programme mentioned earlier, the scenarios are used on one hand to make a selection of proposed adaptation measures, where no regret is a fundamental criterion. In the second instance, they will be used to confront the selected measures using a realistic set of future environmental and socioeconomic conditions, for which a high level of realism is mandatory. The dual perspective of climate information illustrates the need to close the gap between (top–down) climate model-derived

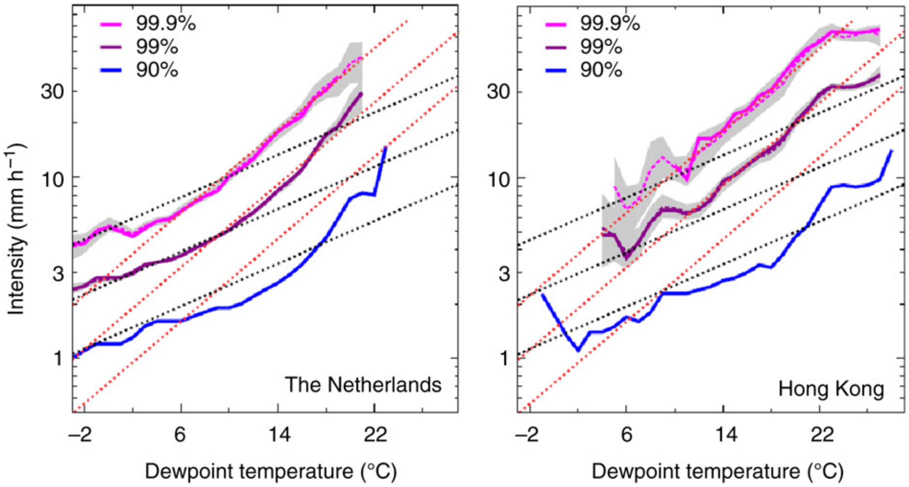

Figure 3 Scaling of hourly precipitation intensity with surface dew-point temperature in the Netherlands and Hong Kong, derived from observations (Lenderink, G., H. Y. Mok, T. C. Lee, and G. J. van Oldenborgh, 2011: Scaling and trends of hourly precipitation extremes in two different climate zones – Hong Kong and the Netherlands. *Hydrol. Earth Syst. Sci. Discuss.*, **8**, 4701–4719, http://dx.doi.org/10.5194/hessd-8-4701-2011). The black dotted line shows the Clausius–Clapeyron scaling of approximately 7% per degree Centigrade, whereas the purple dotted line shows twice this rate increase (14% per degree Centigrade).

information on one hand, and bottom–up information needs at the level of impact assessment and vulnerability analysis on the other. Applied this way, the scenarios help in defining the adaptation tipping points, where the driver for action is not any changes in climate statistics but the inability to meet sustainability and protection criteria. For these, changing climate statistics is only one of the issues, next to socioeconomic developments (Kwadijk et al. 2010). The case studies explored earlier are described as a series of examples of how climate change scenarios can help in making society relevant vulnerability assessments and developing adequate adaptation options. Rather than relying on a single or consensus-based climate model projection, a range of scenarios is constructed with a strong link to the major large-scale drivers of weather phenomena in the Dutch area. They should not be considered as a representation of all possible future climate conditions, but reflect a number of relevant pictures. The standard output variables are inspired by the wide range of sectors that make use of them, with a focus on extremes that have the potential to disrupt society (such as changes in multiday precipitation extremes for the Rhine area). They allow a contextual assessment, by focusing on areas where many people live (in the coastal zone and along the Rhine and Meuse river banks). Although they focus on the climate time scale of half a century and longer, many studies have used them for shorter projection horizons. The new generation of climate change scenarios, KNMInext, will increasingly address this 10–30 year time scale, including a much stronger emphasis on natural weather variability and current trends.

The structure and range of KNMI'06 allows rapid assessments for a wide range of relevant climate conditions, including those to which a specific sector or area is particularly vulnerable. Moreover, the scenarios provide the indispensable structure for an integrated approach that allows comprehensive analysis of the uncertain future climate, and makes optimal use of climate knowledge embedded in theory, models, and observations.

Information transfer between climate science and socioeconomic impact assessment is subject to an optimal update time scale. The time scale of scientific progress is not necessarily compatible with the time scale of policy implications of any changes in climate statistics. Climate change assessments for various sectors in the Dutch Delta often require extensive model simulations and stakeholder involvement. This 'assessment chain' has an inherent inertia that cannot be ignored. This inertia is related not only to the decision-making process chains embedded in operational policy and management practices but also to the fact that climate scenarios should reflect robust scientific findings. Therefore, even highly relevant and well-understood new insights in the scientific arena need to go through a 'time filter' process to avoid unmanageable information inputs in the chain. Guidance of existing climate information therefore is often a more powerful tool to have this information percolate into the management chain than rapid updates of guiding scenarios.

The other side of the chain, the vulnerability assessment, can be typed likewise. Unexpected climate-related impacts (such as an inland dike breach or salt water intrusion due to excessive drought in 2003), (re)assessment of policy implications (such as the influence of flood protection measures in Germany on the design discharge in the Netherlands), or changing economic factors (such as the discount rates relevant for planning long-term investments) all frequently put climate vulnerability in an altered perspective.

An intensive collaboration of Dutch climate scientists and experts in local impact assessment, delta technology, spatial planning, and socioeconomic translation has developed significantly during the past decade. Large infrastructure projects like the Delta Programme and well-designed research and stakeholder participation programs such as Climate Changes Spatial Planning and Knowledge for Climate have helped creating these networks. Future developments will continue to challenge the understanding of the many interactions between climate and human dimensions at multiple scales, and will continue to call for this kind of research networks.

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5.18 Epitomes of Bottom-Up Hydro-Geo-Climatological Analysis to Face Sea Level Rise in Complex Coastal Ecosystems

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5.18.1 Coastal Ecosystems: Geomorphic Elements, Species, and Cities

A coastal ecosystem includes estuaries, coastal waters, and lands located at the lower end of drainage basins, where stream and river systems meet the sea and are mixed by tides. The coastal ecosystem includes saline, brackish (mixed saline and fresh), and fresh waters, as well as coastlines and the adjacent lands. All these water and landforms interact as integrated ecological units. Shorelands, dunes, offshore islands, barrier islands, headlands, lagoons, and freshwater wetlands within estuarine drainages are included in the definition of coastal ecosystem since these interrelated features are crucial to coastal wildlife and their habitats. A variety of animals and plants complete the ecological system. The definition of coastal ecosystem may also potentially apply to lacustrine areas, where bodies of freshwater play an ecological role similar to oceans. For instance, bird populations of the same species are found both in lacustrine and coastal ecosystems. This is the case of the Snowy Plover, for example, that is found along the shores of inland lakes in the United States and along the west coast of Florida and California (Convertino et al. 2011a). The aforementioned definition of coastal ecosystem considers only the environmental features of coastal ecosystems. However, 'anthromes' are part of coastal ecosystems. Anthromes represent the global ecological patterns created by sustained direct human interactions with ecosystems. Thus, anthromes are focused on the human components of ecosystems rather than on their natural components. Therefore, a comprehensive definition and analysis of coastal ecosystems, including biomes and anthromes together, seems fundamentally important for better projections of climatic change effects and management scenarios. This involves the use of integrated modeling frameworks and translates into better decision-making evaluation of alternatives to face climatic change (Kiker et al. 2005; ECA 2011; Karvetski et al. 2011).

In the following, we focus our attention on the relationships between hydrological, ecological, and climatological variables of two coastal ecosystems in which the biotic and the anthropic components exert a prevalent role, respectively: Florida (Gulf of Mexico coast) for the former case and Venice (Italy) for the latter case. Figure 1 shows the two case studies under flooding events: St. Marco Square in Venice and Santa Rosa Island in Florida. In both cases, flooding phenomena, which are mostly triggered by different climatological stressors, produce relevant economic losses to the coastal ecosystem. For the Gulf Coast of Florida, we focused our attention on the effect of floods on long-term wetland evolution and risk assessment of shorebirds, while for Venice we investigated the effects of the pressure–wind combination on tidal levels in the city. Florida and Venice can be thought of as a complex of human and natural systems at different scales strongly affected by sea level rise (SLR). Here, the focus is on the natural component of the Florida ecosystem and on the human component of the Venice ecosystem. Nonetheless, SLR also affects species in the Venice lagoon (Marani et al. 2004, 2007, 2010) and urbanized cities along the coast of Florida (Elsner et al. 2008; Weiss et al. 2011).

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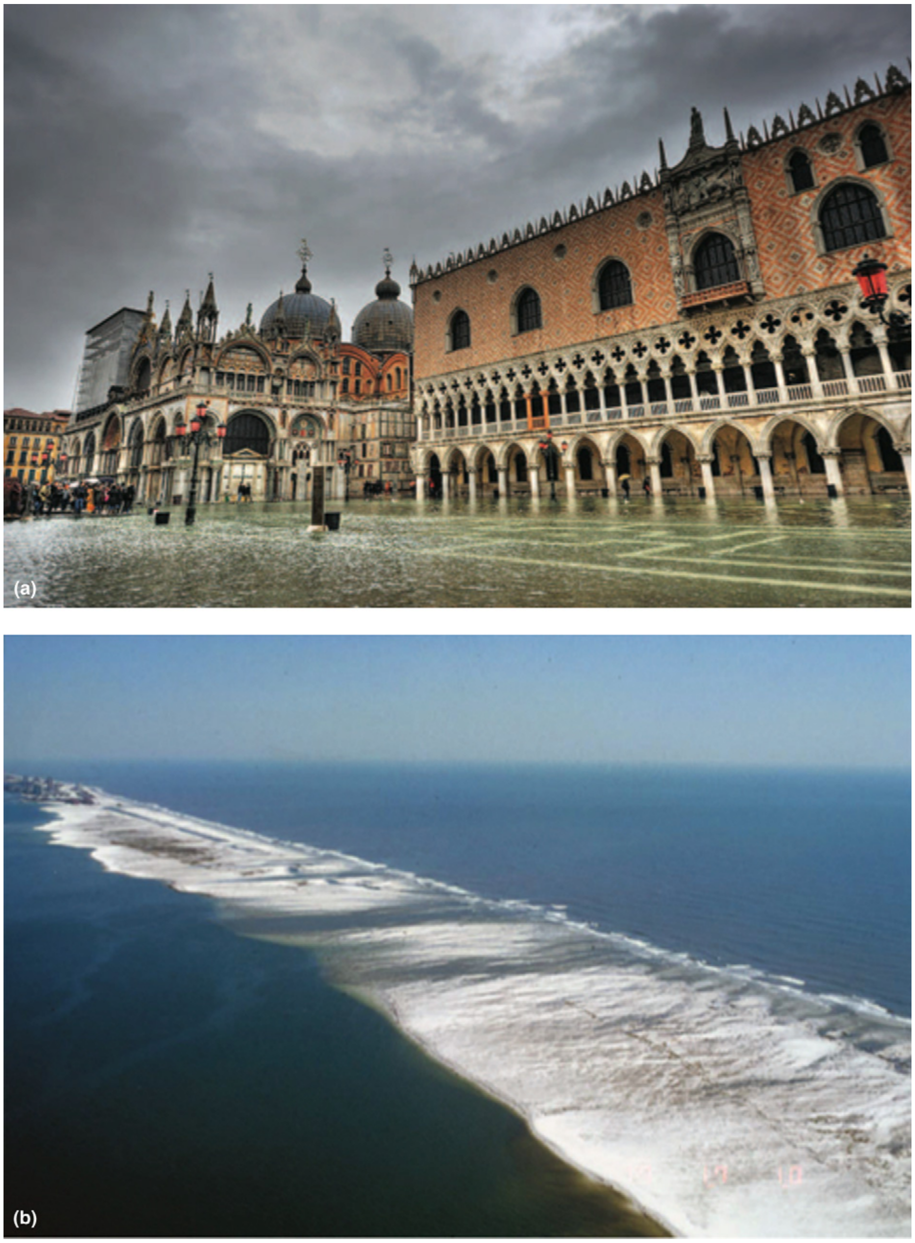


Figure 1 Coastal ecosystems subjected to inundation phenomena. (a) St. Marco Square flooded in November 2008. (b) Overwash over an undeveloped Santa Rosa Island, Florida.

5.18.2 Materials and Methods

5.18.2.1 Global Sea Level Rise, Local Sea Level Rise, and Storm-Related Stressors

Global SLR due to climatic change would affect many sensitive coastal areas around the world.

An increasing long-term linear trend of SLR has been observed; however, in recent years sea level has actually reduced the speed of its increase. Thus, SLR is clearly not accelerating, but it appears to increase (Rohling et al. 2008; Church and White 2011). It is estimated that almost 50% of the worldwide population live along or nearby coastal areas within 100 km from the coastline (WRI 2000; SEDAC 2011). Thus, there is the urgent need to understand how climate affects coastal areas and how to design protection interventions to limit damages to human and natural components of coastal ecosystems.

We define in the following some hydrological phenomena potentially affected by SLR. These processes are useful in the analysis of the Florida and Venice case studies. Although there are similarities, these processes tend to be treated separately because of their partial independency.

Local mean sea level (LMSL) is defined as the height of the sea with respect to a land benchmark, averaged over a period of time (such as a month or a year typically) long enough that fluctuations caused by waves and tides are smoothed out. Eustatic change (as opposed to local change) results in an alteration to the global sea levels, such as changes in the volume of water in the world oceans or changes in the volume of an ocean basin. We will refer to the latter as global SLR.

Overwash is the flow of water and sediment over the crest of the beach that does not directly return to the water body (such as ocean, sea, bay, or lake; hereafter, ocean) where it originated after water level fluctuations return to normal. There are two kinds of overwashes: overwash by runup and overwash by inundation.

Tides are the rise and fall of sea levels caused by the combined effects of the gravitational forces exerted by the Moon the Sun, and the rotation of the Earth. While tides are usually the largest source of short-term sea level fluctuations, sea levels are also subject to forces such as wind and barometric pressure changes, resulting in storm surges, especially in shallow seas and near coasts.

A storm surge is an offshore rise of water associated with a low-pressure weather system, typically tropical cyclones and strong extratropical cyclones. Storm surges are caused primarily by high winds pushing on the ocean's surface. The wind causes the water to pile up higher than the ordinary sea level. Low pressure at the center of a weather system also has a small secondary effect, as can the bathymetry of the body of water. It is this combined effect of low pressure and persistent wind over a shallow water body that is the most common cause of storm surge flooding problems. The term 'storm surge' in casual (nonscientific) use is storm tide; that is, it refers to the rise of water associated with the storm, plus tide, wave run-up, and freshwater flooding.

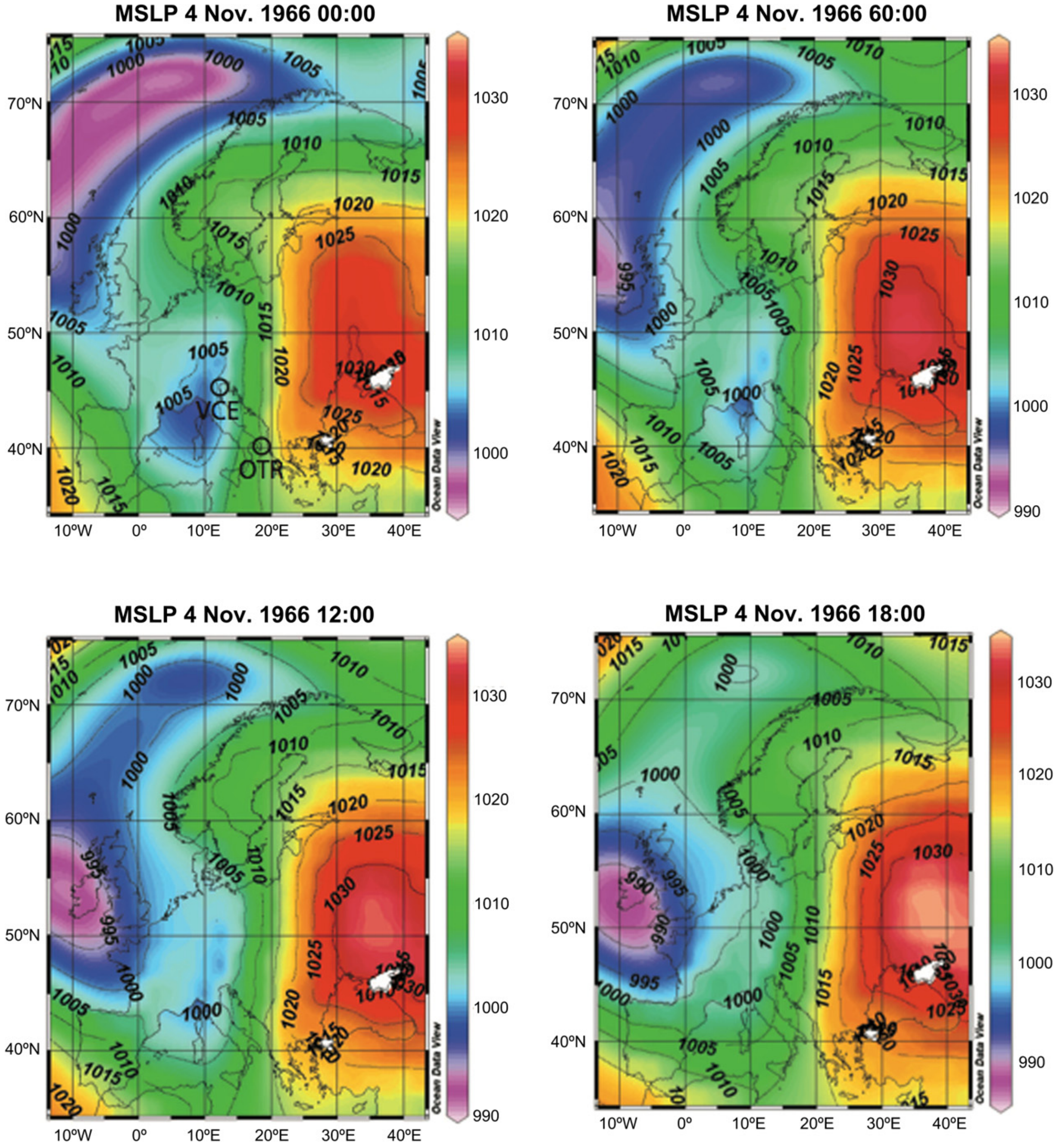
A hydroperiod can be defined as the number of days per year that an area of land is wet or the length of time that there is standing water at a location.

5.18.2.2 Florida and Venice: Similarities and Contrasting Elements

In Venice, exceptional tides (when the waterline is equal to or more than 140 cm on the mareographic zero of 'Punta della Salute,' located near the Salute Church, in front of St. Mark's Square (Carbognin et al. 2010)) statistically occur once every 4 years. Exceptional tides are caused by a combination of various factors, such as the astronomical tide, low pressure on the Tyrrhenian Sea, strong south wind ('Scirocco'), and the Adriatic seiche. Further, two larger phenomena also contribute to the increase in the water level: eustasy and the subsidence of the Venetian Lagoon, which, together, have caused an altimetric loss of about 26 cm in the past century (Gambolati et al. 1974; Rinaldo et al. 2008; Carbognin et al. 2010). High water depends on the tide cycle (the alternation of high and low tides happens every 6 h): when there is 'acqua alta' (high water) on the streets, it lasts only a few hours during the peak of the high tide (usually 3–4 h). Once water goes down, things go back to normality. On average, Venice is characterized by a semidiurnal tide (tidal period $T = 12.4$ h) and lagoon microtidal (tidal amplitude $a = 0.5$ m) extending over an area of roughly 550 km^2 (Rinaldo et al. 2008; Toffolon and Lanzoni 2010). Four big flooding events are in the memory of Venice inhabitants (Rinaldo 2009): the 194-cm high water (meteorological tidal level) event in November 1966 at 12:00 p.m., the 158-cm event in February 1986 at 00:00 a.m., the 142-cm event on 8 December 1992 at 00:00 a.m., and the 144-cm event in November 2000 at 6:00 p.m. In 1966, an unusual combination of high tides and a relentless sirocco wind sent floodwaters surging through the city's canals and spilling over into its historic palaces and piazzas. Priceless art works were ruined, and thousands of people were trapped in their homes (Rinaldo 2009). Another 5000 were left homeless. The 'great flood' in 1966 sparked an intense debate on how to save the World Heritage city from the ravages of flooding (Gambolati et al. 1974; Harleman et al. 2000; Bras et al. 2001; Pirazzoli and Umgiesser 2003; Comerlati et al. 2004; Castelletto et al. 2008; Rinaldo 2009). The final solution was the design and construction of the 'Mo.S.E' ('Modulo Sperimentale Elettromeccanico'; in English, 'Experimental Electromechanical Module') consisting of rows of mobile gates able to isolate the Venetian Lagoon from the Adriatic Sea when the tide reaches above an established level (110 cm) and up to a maximum of 3 m. The Mo.S.E. is going to be in fully operative in 2012 (Carbognin et al. 2010). We considered the 1966, 1986, 1992, and 2000 events in our analysis. Two other events, which happened on 1 December 2008 and 25 December 2009, registered a tidal level of 156 cm and 145 cm, respectively. However, the latter events were not considered for the lack of wind data. Figures 2 and 3 show the global circulation patterns of pressure and wind velocity for the 1966 high-water event.

The tidal cycle in Florida has been much less studied than in Venice. However, the tidal excursion in the Gulf of Mexico is quite moderate with respect to that in Venice. In the Gulf of Mexico for the semidiurnal tides, the times of maximum tidal current generally lead the high tide at St. Petersburg (Florida) by 2–9 h. On the other hand, the maximum tidal currents of the diurnal tide lag the high tide time at St. Petersburg by 10–20 h (He and Weisberg 2002). The east coast of Florida (Atlantic Ocean) exhibits semidiurnal tides, whereas most of the west coast of Florida exhibits mixed tides and most of the Panhandle of Florida Gulf Coast has diurnal tides. While in Venice the persistence of the pressure gradient over the Adriatic Sea is mainly responsible for the enhanced tides, in Florida tropical cyclones are responsible for the overwash phenomena. A tropical cyclone is a storm system characterized by a large low pressure center and numerous thunderstorms that produce strong winds and heavy rain. Florida is consistently affected by tropical cyclones of different categories (from tropical depression to hurricanes) in the summer season. The 2004 Atlantic hurricane season officially began on 1 June 2004 and lasted until 30 November 2004. These dates conventionally delimit the period of each year when most tropical cyclones form in the Atlantic basin. The season was notable as one of the deadliest and costliest Atlantic hurricane seasons on record in the past decade, with at least 3132 deaths and roughly 50 billion (2004 USD; 58.1 billion 2011 USD) in damage. The most notable storms for the season were the five named storms that made landfall in the US state of Florida, three of them with at least 115 mph (185 km h^{-1}) sustained winds: Hurricanes Charley, Frances, Ivan, and Jeanne, and Tropical Storm Bonnie. This is the only time in recorded history that four hurricanes affected Florida.

Thus, pressure gradients and wind velocity with different magnitudes affect Florida and Venice, causing enhanced flooding phenomena. Florida is typically characterized by low-frequency, very intense vertical pressure gradients that form in


MSLP 4 Nov. 1966 00:00

MSLP 4 Nov. 1966 60:00

MSLP 4 Nov. 1966 12:00

MSLP 4 Nov. 1966 18:00

Figure 2 Mean sea level pressure for 4 November 1966; 6-h global circulation patterns for the mean sea level pressure (MSLP) over Europe measured in hectopascals (from 00:00 to 18:00 clockwise).

the ocean and moves inland with high speed in the summer season. On the contrary, Venice is characterized by medium low-frequency pressure gradients over a large area and moderate wind speed in the winter season.

5.18.3 Results and Discussion

5.18.3.1 Venice: Tide and Storm Surge

The climatological and hydrological drivers of the 'high water' phenomena in Venice have been analyzed. The first objective was to perform a comparative analysis of the ERA-40 reanalysis (ERA40 2011), simulation data, observations of wind velocity, mean sea level pressure (MSLP), and tidal levels and to detect the key variables for 'high water' forecasting. The effort was in analyzing global patterns from maps and time series of meteorological variables. We found that, for the MSLP, the observed and ERA-40 values are in agreement, while for the wind velocity, ERA-40 overestimates or underestimates the observed values. We also found evidence of correlations between the MSLP gradient, wind velocity, and meteorological tidal level.

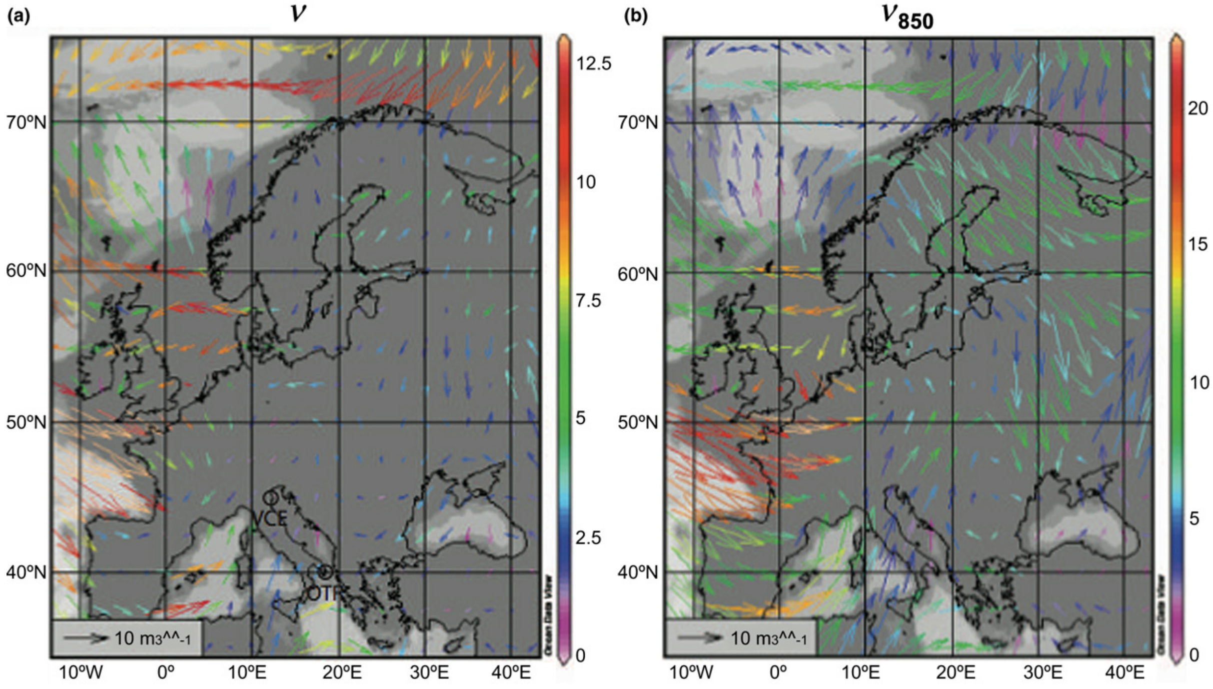


Figure 3 Wind velocity for 4 November 1966. Global circulation patterns (a) for the wind velocity at surface and (b) at 850 hPa (v and $v850$) (m s^{-1}) over Europe (at 12:00).

A concurrence of MSLP gradient, wind velocity, and high water peaks was observed. The second objective was to detect changes in the signatures of flooding phenomena in Venice and to relate them to global atmospheric circulation patterns (Figures 2 and 3). Previous analysis of the tidal regime in Venice during the past century showed that the frequency and magnitude of high tides are correlated to interdecadal climatic oscillations (Fagherazzi et al. 2005; Rinaldo et al. 2008; Rossa et al. 2010).

Figure 4 shows the wind speed at 850 hPa and at surface (m s^{-1}), the MSLP p (Pa), and the tidal level TL (cm) for Venice (green dots) and Otranto (red dots) on 4 November 1966. There is a strong correlation among wind velocities, pressures, and tidal level in Venice. The pressure–velocity–tidal level pattern is remarkably observed also for the 1986, 1992, and 2000 events. The wind velocities at the surface in Venice and Otranto are quite similar; however, the wind velocity at 850 hPa is predominantly higher in Otranto than in Venice. This contributes to the storm surge in Venice and is also a by-product of the pressure gradient Otranto–Venice. There was a peak in the velocity and pressure and, consequently, after a negligible delay, a peak in the tidal level.

Figure 5 reports the ERA-40 reanalysis and the observed pressure gradient over the Adriatic Sea (Otranto–Venice) of the 4 November 1966 event. The ERA-40 reanalysis is capable of representing on average the observed pressure gradient. However, the ERA-40 reanalysis velocity (both at surface and at 850 hPa) underestimated the observed velocity (Figure 4). The temporal recurrence of the wind velocity vs. the Otranto–Venice pressure gradient is shown in Figure 6 for the 1966, 1986, 1992, and 2000 events. $v \sim 1.9\Delta p$ and $v850 \sim 0.8\Delta p$ are the linear relationships assessed for the velocity and surface and at 850 hPa with coefficient of determination R^2 equal to 0.46 and 0.68, respectively.

Figure 7 shows the negative correlation between the tidal level and MSLP in Venice for the month of November from 1924 to 2001. For a low MSLP, a high value of tidal level is observed and vice versa. The correlation coefficient is 0.61. For a low MSLP in Venice, a high MSLP is observed in Otranto. The difference in pressure between the two cities creates the pressure gradient responsible for the storm surge in Venice. Figure 8 shows a comparison between modeled (ERA-40 reanalysis) and observed wind velocity at surface and MSLP for Venice in 1966, 1986, 1992, and 2000. The plots show that ERA-40 underestimates and overestimates the observed velocity without a particular trend. This was already evidenced in Figures 4 and 5. As for the MSLP – in this case in Venice – ERA-40 reproduces the observed MSLP extremely well. R^2 is 0.52 and 0.93 for the regressions in Figure 8, top and bottom plots, respectively.

Regardless of the persistency of the pressure gradient Otranto–Venice – demonstrated for all the ‘acqua alta’ events considered – recent studies found that the frequency of extreme storm surge events affecting Venice is projected to decrease by about 30% by the end of the twenty-first century (Troccoli et al. 2011). In addition, a trend assessment based on tidal observations by Troccoli et al. (2011) found a reduction in extreme tidal levels. Extrapolating the current +17 cm per century sea level trend, these results suggested that the frequency of extreme tides in Venice might largely remain unaltered under the projected twenty-first century climate simulations.

5.18.3.2 Florida: Habitat Overwash, Tropical Cyclones, and Species Risk Assessment

Florida coastline-dependent species are characterized by a very high potential of extirpation risk because of SLR

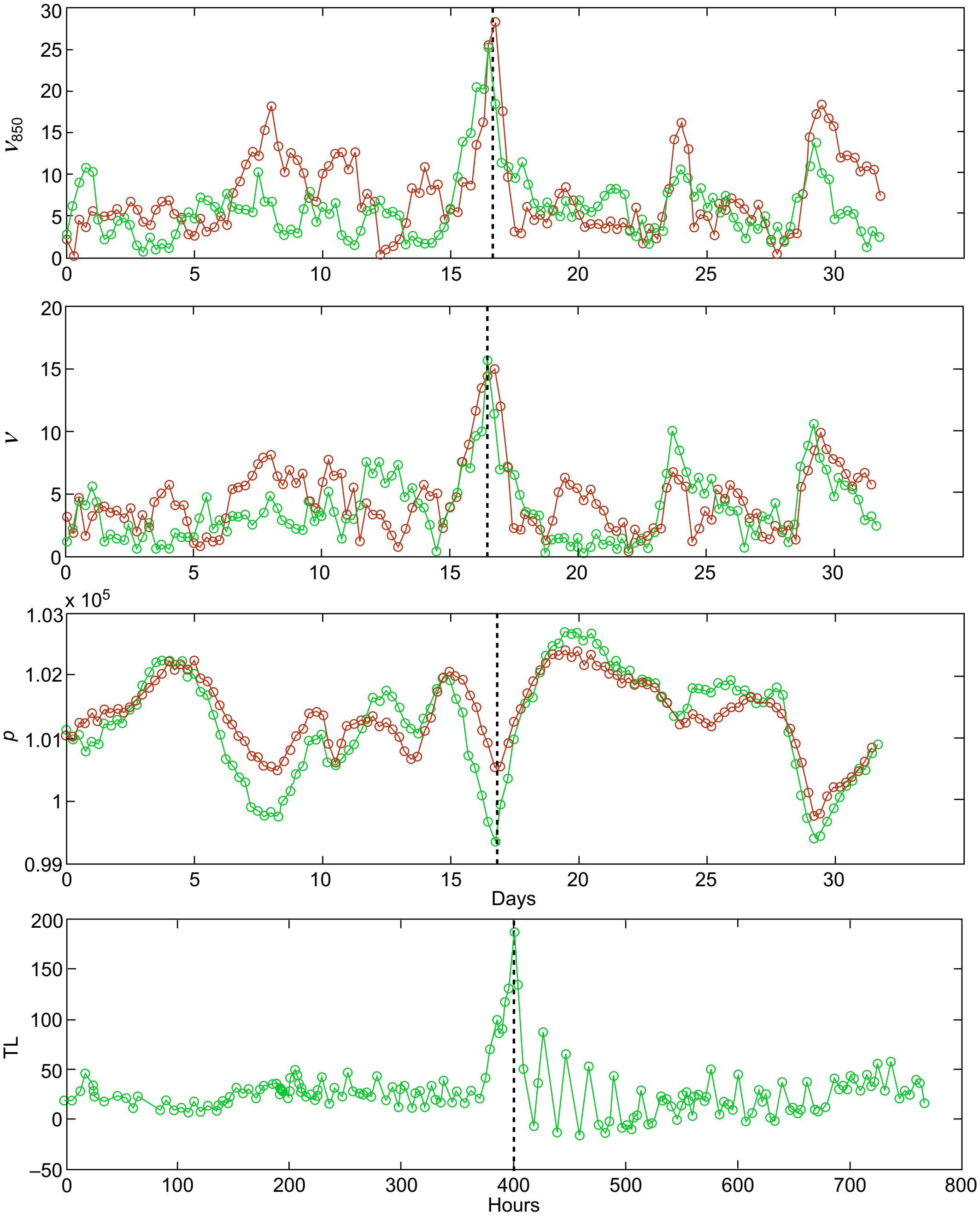


Figure 4 Correlation among global climatological variables and local hydrological variables. Wind speed at 850 hPa and at surface (m s^{-1}), mean sea level pressure p (Pa), and tidal level TL (cm) for Venice (green dots) and Otranto (red dots) on 4 November 1966.

(Aiello-Lammens et al. 2011) and a possible future increase in tropical cyclone activity (Convertino et al. 2011b) The Snowy Plover (*Charadrius alexandrinus nivosus*, SP) (**Figure 9**) is a threatened species resident in Florida and was considered as a sentinel species to understand the effect of climate on the Florida coastal ecosystem (Convertino et al. 2011c). The geographic range of the Snowy Plover is along the Gulf of Mexico coast of Florida; thus, we considered only this region in the modeling effort. Through the Strategic Environmental Research and Development Program (SERDP) SI-1699 (Linkov 2009; Convertino et al. 2011c) led by the US Army Engineer Research and Development Center and the University of Florida we integrated a land-cover model (Sea Level Affecting Marshes Model (SLAMM)) (Clough 2010), a habitat suitability model (MaxEnt) (Phillips and Miroslav 2008), and an ecological metapopulation model (RAMAS) (Akcakaya 2005). We predicted the geomorphological changes of the Gulf of Mexico coastal habitat in Florida, assessed the habitat suitability of the Snowy Plover, and calculated the Snowy Plover extirpation risk at relevant time and spatial scales in 2100

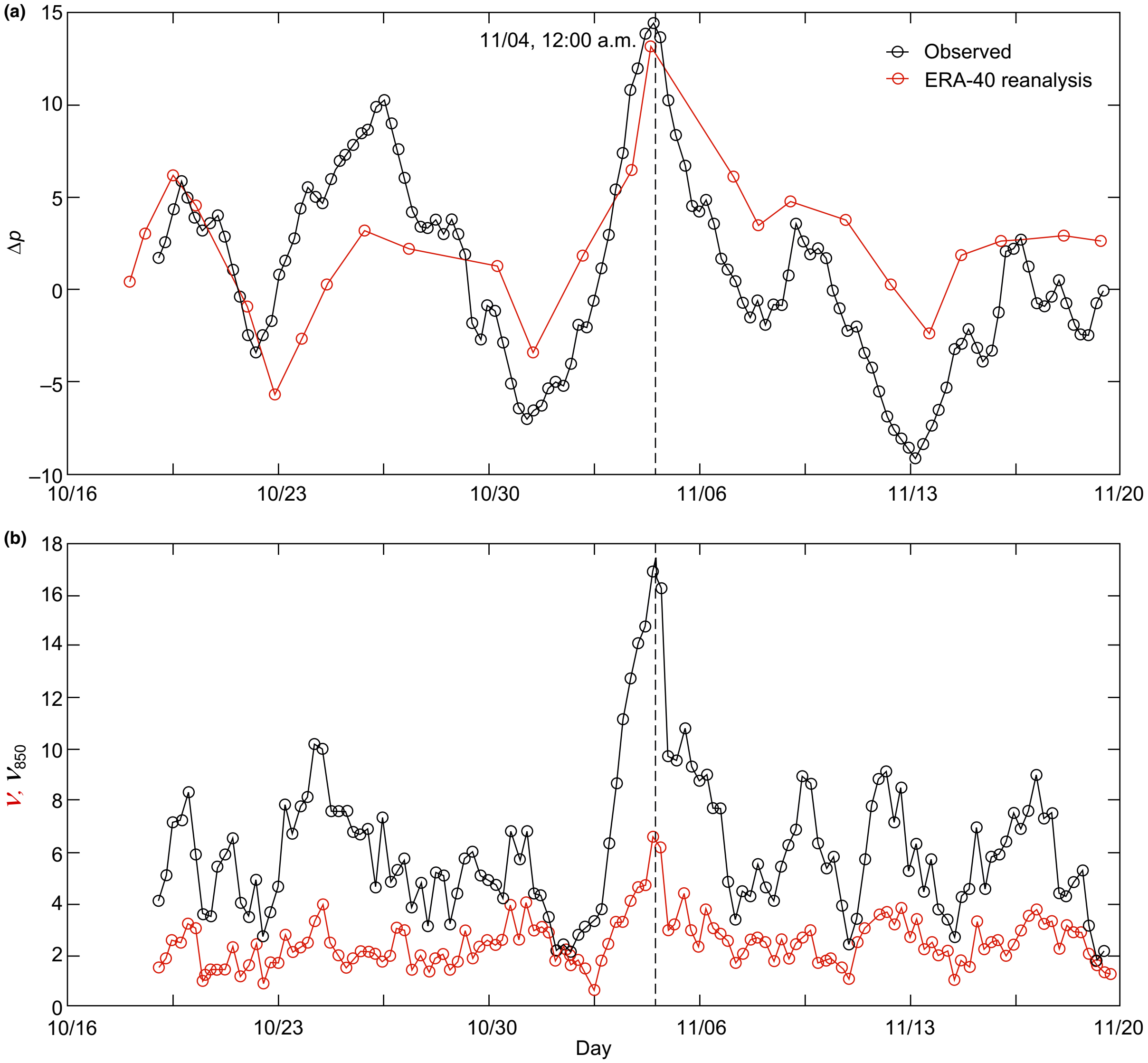


Figure 5 Intermonthly pressure gradient and wind velocity for the 4 November 1966 event. (a) ERA-40 reanalysis and observed pressure gradient over the Adriatic sea (Otranto–Venice). (b) ERA-40 reanalysis wind velocity at surface and at 850 hPa for Venice.

(Convertino et al. 2011d; Chu-Agor et al. 2011a; Aiello-Lammens et al. 2011). Particular attention was given to testing the uncertainty of the projections related to the model input factors (see Section 5.18.3.4) and to verify a priori assumptions and modeling results among climatological, geomorphological, and ecological variables.

In particular, Convertino et al. (2011a,b) investigated the relationship between the probabilities of the presence of a nesting ground of the Snowy Plover and tropical cyclone occurrence and between the probability of the absence of a nesting ground and renourishment interventions occurrence. A Bayesian inference was utilized considering the historical occurrences of the Snowy Plover nests, the historical Atlantic cyclones, and the renourishment interventions (Figure 9). The odds ratio was defined as the ratio of the odds of a nesting ground in the spring following a year with at least one tropical cyclone to the odds of a nesting ground in the spring following a year without a tropical cyclone. The frequencies were based on 104 Monte Carlo samples. The median odds ratio – considering nesting grounds and cyclones – is 7, and the mean is 11. The maximum likelihood estimate is a lognormal distribution (red curve), and the coefficient of determination is $R^2 = 0.87$ (Figure 10(a)). Figure 10(b) shows the posterior probabilities of absence of the odds ratio – considering nesting grounds and renourishments – in the breeding season. The odds ratio is in this case the ratio of the odds of a nesting ground in the spring following a year with at least one renourishment event to the odds of a nesting ground in the spring following a year without a renourishment intervention. For the breeding season, the median odds ratio is 2.5 and the mean is 4.9. The maximum likelihood estimate is a lognormal distribution, and the coefficient of determination is $R^2 = 0.92$.

The higher percentage of flat areas on the beach, created by cyclones, that translates to an increased open view of the

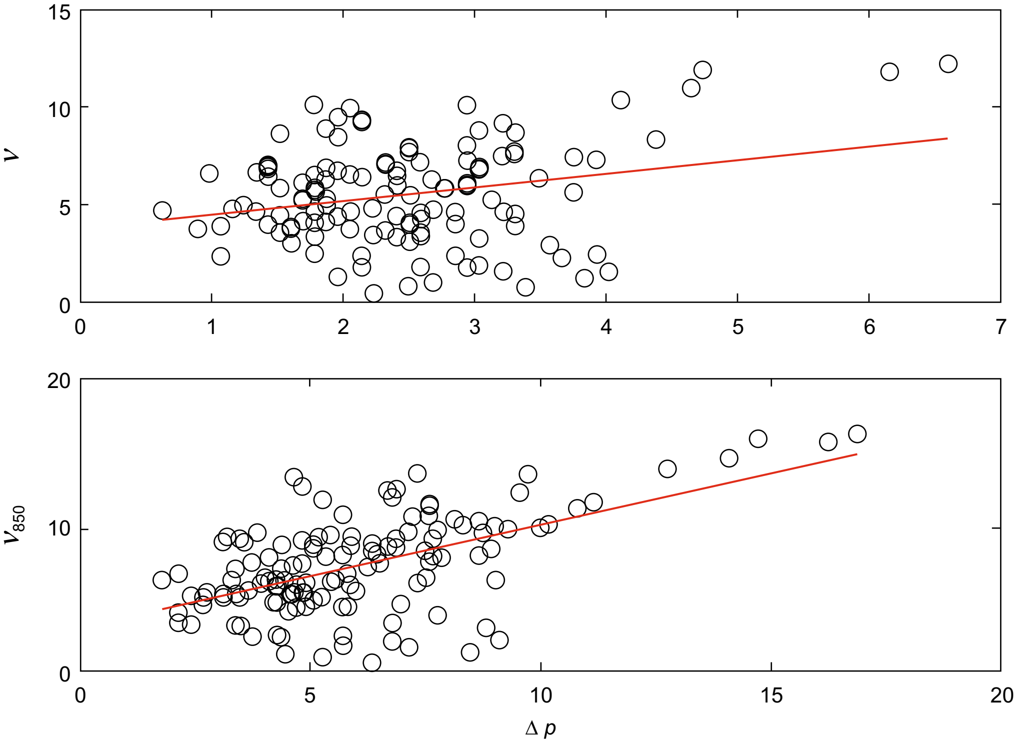


Figure 6 Wind velocity vs. observed pressure gradient for the 1966, 1986, 1992, and 2000 events. Wind speed at surface and at 850 hPa in Venice vs. the pressure gradient Otranto–Venice. The coefficient of determination R^2 is 0.46 and 0.68 for the former and the latter regression, respectively.

habitat (Gornish and Miller 2010), the presence of diffuse debris, and the large amount of organic material on the beach increase the favorability of the shores to be a breeding ground for the Snowy Plover (Convertino et al. 2011d). As for the renourishments, we argued that the decrease in the documented nest abundance of the Snowy Plover resulted from an altered cross-sectional beach profile, which is not favorable for nesting and foraging. As a consequence, nesting success is reduced because of habitat modifications and possible direct disturbance of renourishment interventions.

The quantified positive and negative feedbacks between the Snowy Plover, tropical cyclones, and renourishments are very useful in metapopulation modeling. In fact, metapopulation models (e.g., RAMAS) also reproduce stochastic events like cyclones and their effect on the modeled species. We disregarded the hypothesis of the catastrophic effect of cyclones on the Snowy Plover; thus, we avoided underestimating the abundance of nesting grounds of the species in time.

5.18.3.3 Wetland Evolution and Two-Dimensional Flood Modeling

Flooding risk maps are a key component of risk management of coastal areas (Grimaldi et al. 2009). Effective shoreline management planning requires broad-scale and long-term coastal flood risk analysis (Harvard Business School 2007).

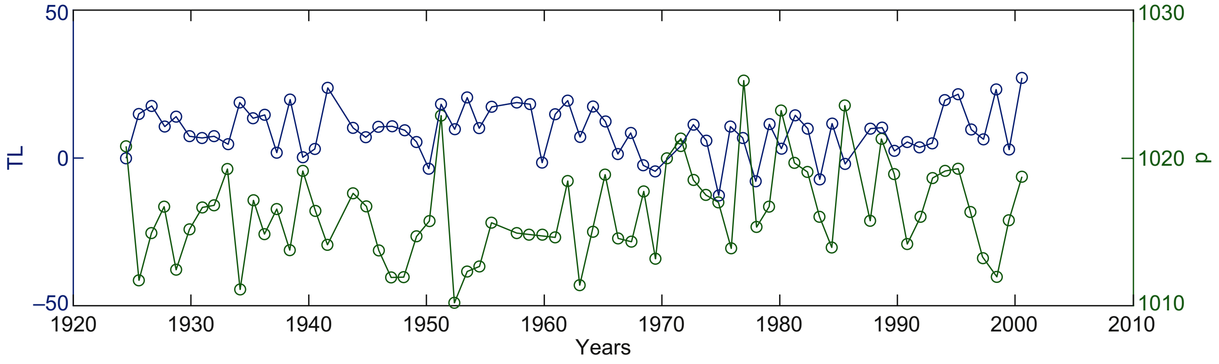


Figure 7 Tidal level vs. monthly averaged MSLP for November from 1924 to 2001. The tidal level (cm) and the monthly averaged MSLP for Venice are compared through the years.

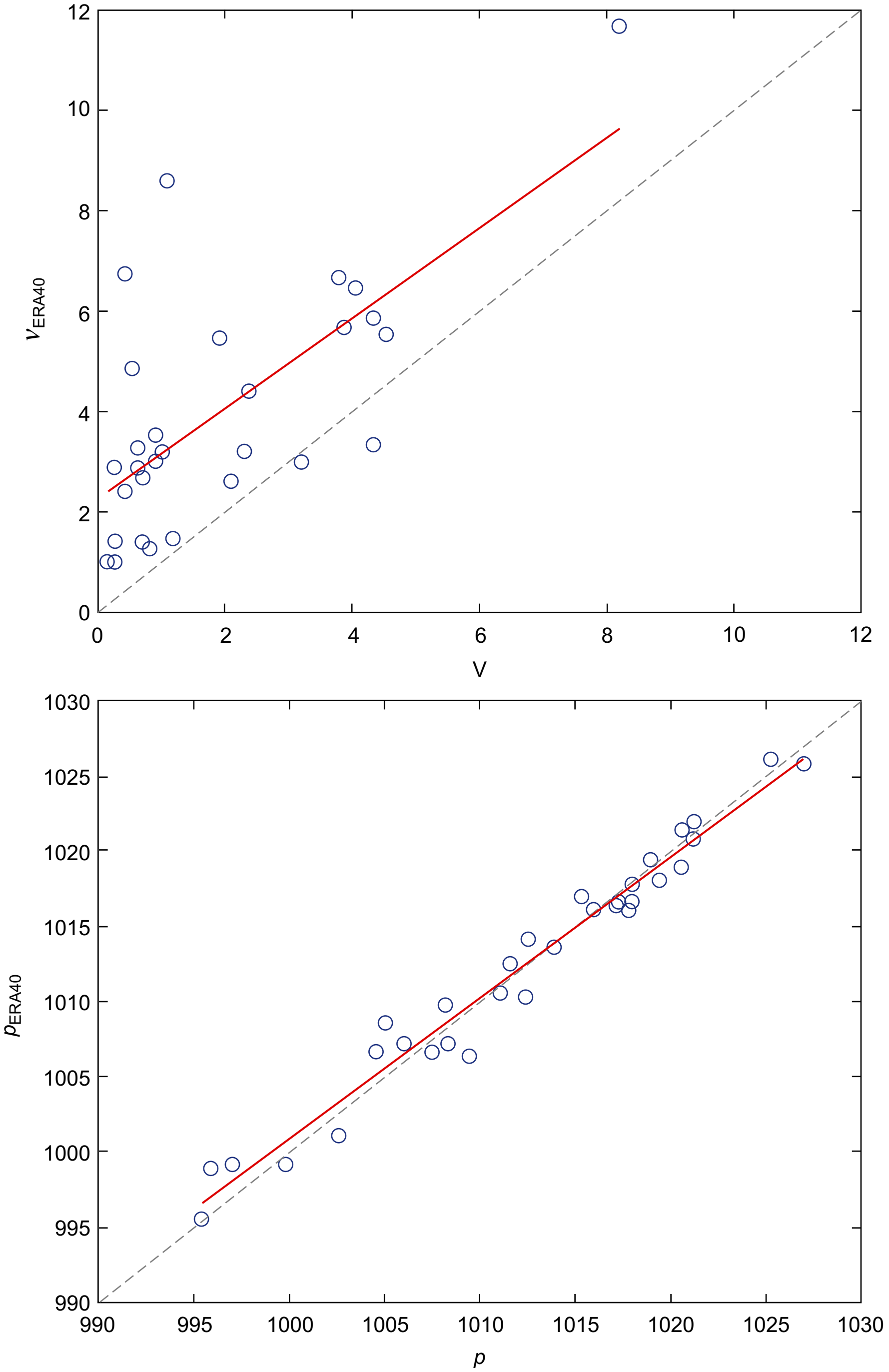
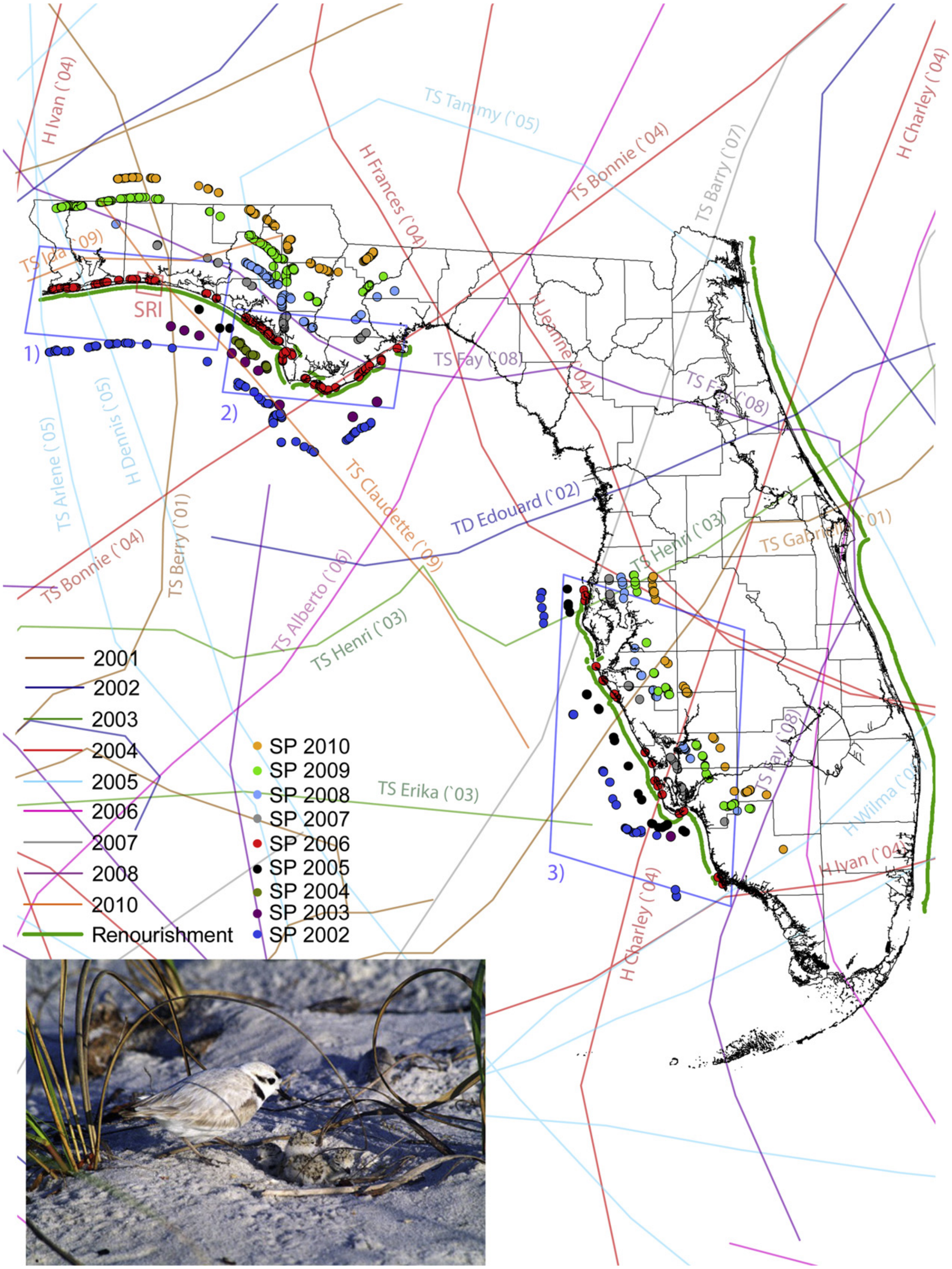


Figure 8 ERA-40 reanalysis vs. observed wind velocity and mean sea level pressure. The graphs show a comparison between modeled and observed wind velocity at surface and MSLP for Venice in 1966, 1986, 1992, and 2000.

Such work has become more necessary, and challenging, as SLR and changes in other climatic variables have become more evident. Coastal boundary conditions tend to complicate flood risk analysis. In particular, the close coupling between flooding and shore morphology introduces considerable uncertainty, because beach level is a major determinant in the reliability of flood protection structures and suitability of the habitat for species.

For operational purposes, most flood inundation modeling is carried out using one-dimensional (1D) and pseudo-2D methods (1D for river segments and 2D for open areas such as estuaries/delta, ocean, and floodplains). As for our Florida study, the habitat considered for modeling was derived by an inundation scenario that does consider the heterogeneities in the elevation of lands when inundated but not the presence of infrastructure. For safety purpose, a hypothetical 10-km


H Ivan (`04)
TS Tammy (`05)
H Frances (`04)
TS Bonnie (`04)
TS Barry (`07)
H Charley (`04)
TS Ida (`09)
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2)
TS Fay (`08)
TS Fay (`08)
TS Arlene (`05)
H Dennis (`05)
TS Berry (`01)
TS Claudette (`09)
TD Edouard (`02)
TS Henri (`03)
TS Gabrielle (`01)
TS Bonnie (`04)
TS Alberto (`06)
TS Henri (`03)
TS Erika (`03)
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2001
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Figure 9 Snowy Plover nests, cyclones, and renourishments in Florida. Nesting dataset of Snowy Plovers from 2002 to 2010 (dots) and tracks of the tropical cyclones (tropical depression (TD), tropical storm (TS), hurricane (H)) in the period 2001–09 from NOAA (2010) of the North Atlantic tropical cyclone database. The renourishment projects in Florida have been represented (Convertino et al. 2011b). A Snowy Plover is in the picture in the lower left corner. (1) is the Northwest Florida region (Santa Rosa Island (SRI) is included), (2) is the Apalachee Bay region, and (3) is the Southwest Florida region. [Available online at htttp://www.plosone.org/article/info:doi/10.1371/journal.pone.0015683.]

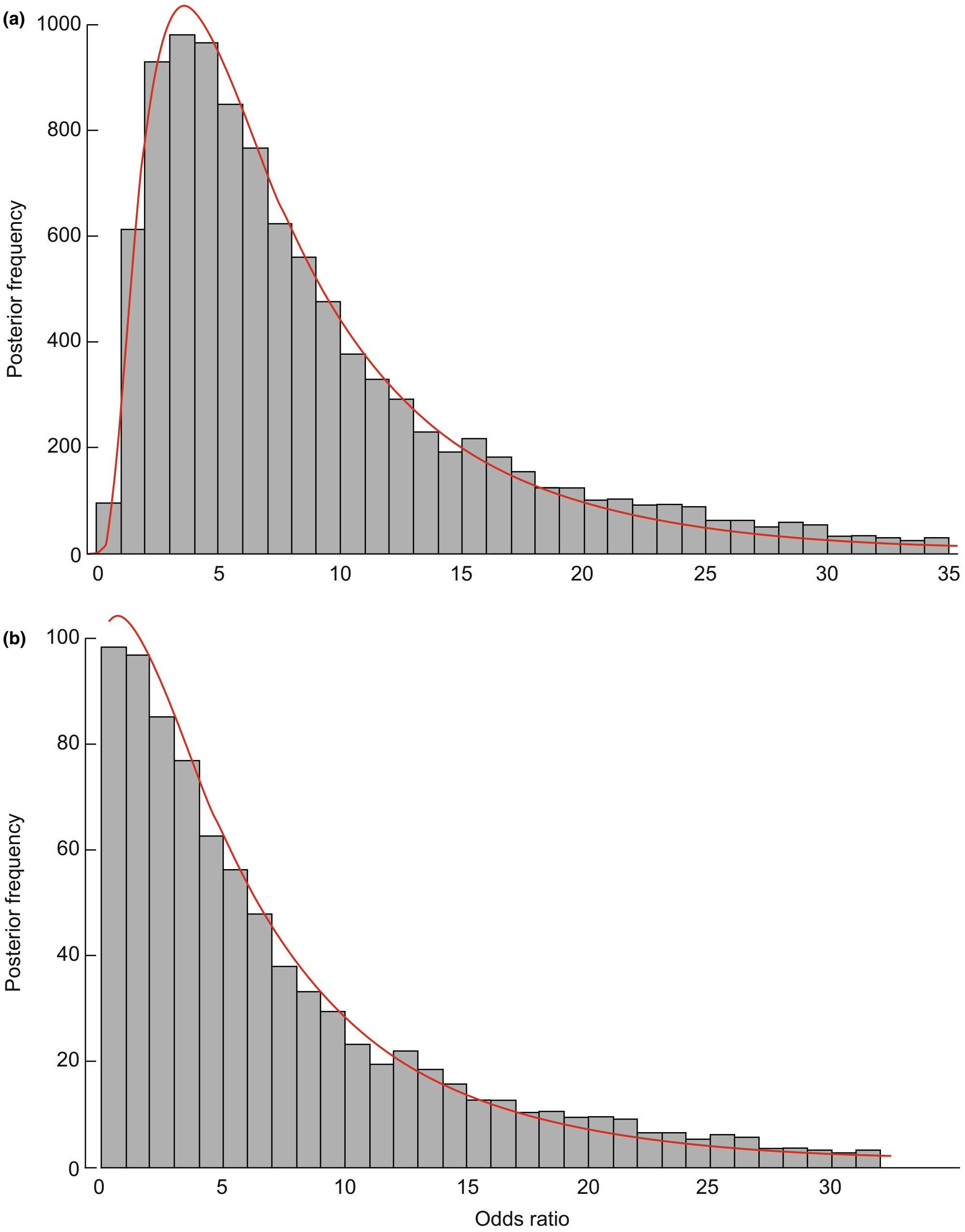

Figure 10 Bayesian estimation of probability of occurrence of a Snowy Plover nest. (a) Posterior frequencies (of presence) of the odds ratio between the odds of a breeding ground in the spring following a year with at least one tropical cyclone to the odds of a breeding ground in the spring following a year without a tropical cyclone (Convertino et al. 2011b). [Available online at http://www.plosone.org/article/info:doi/10.1371/journal.pone.00156]. (b) Posterior frequencies (of absence) of the odds ratio in the breeding season between the odds of a breeding ground in the spring following a year with at least one renourishment event to the odds of a breeding ground in the spring following a year without a renourishment intervention (Convertino et al. 2011a). Reproduced from Convertino M., J. F. Donoghue, M. L. Chu-Agor, G. A. Kiker, R. Munõz-Carpena, R. A. Fischer, and I. Linkov, 2011a: Anthropogenic renourishment feedback on shorebirds: a multi- species Bayesian perspective. *J. Ecol. Eng.*, 37, 1184–1194.

inundation distance from the coast was considered as inundation scenario in 2100 (Convertino et al. 2011d). The habitat within this distance was modeled using the land-cover model SLAMM. SLAMM considers a fixed inundation depth, for each SLR value for each year over the domain. This assumption is notoriously physically unrealistic; thus, an elevation-dependent inundation depth would be desirable to predict realistic inundation scenarios. Figure 11 shows a typical SLAMM land-cover output for the Santa Rosa Island along the north Gulf of Mexico coast of Florida (Figure 9). Figure 12(c) shows the changes in the area of the beach habitat that consists of estuarine beach, tidal flat, and ocean beach (constituted of alkaline medium/fine white sand and silt) for the Santa Rosa Island at different SLR scenarios ((0.2; 2.0) m) (Chu-Agor et al. 2011a).

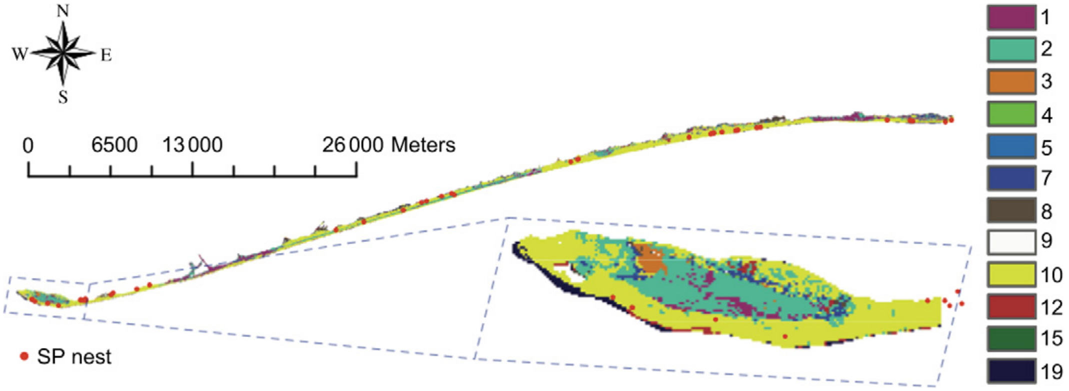

Figure 11 Ecosystem composition for the Santa Rosa Island in 2006. The land-cover classes for the Santa Rosa Island (SRI) are developed dryland (1), undeveloped dryland (2), swamp (3), cypress swamp (4), inland fresh marsh (5), scrub/shrub-transitional marsh (7), salt marsh (8), mangrove (9), estuarine beach (10), ocean beach (12), inland open water (15), and open ocean (19). The red dots are the 2006 nest occurrences of the Snowy Plover that has been taken as the 'sentinel species' of SLR in the SERDP Project 1699.

The beach habitat (composed of estuarine beach, tidal flat, and ocean beach), which occupies 1.4% (2683 ha) of the Eglin Air Force Base (AFB), is one of the most important habitat class for the Snowy Plover population. Eglin AFB hosts about 20% of the overall Snowy Plover population in Florida. As expected, the beach habitat posted an increase in area gained from the losses in higher elevation habitats (most probably marshes) (Chu-Agor et al. 2011a). For the first 30 years (2010–40), the beach is expected to increase by a maximum amount of 3% (81 ha). However, from 2050 forward, the area will decrease gradually until the end of the century, posting a net gain of 2.0% (54 ha). It is surprising to note that the different SLR projections have the same effects on beach habitat (Figure 12) despite the fact that the beach interfaces with the ocean (Chu-Agor et al. 2011a). For modeling the whole Gulf Coast of Florida, the SLR curve of the Intergovernmental Panel on Climate Change (IPCC) A1B (IPCC 2001) scenario was rescaled, fixing a 2-m SLR in 2100 (Figure 12(a)). Values of SLR are constant over the modeled domain extended 10 km from the coast.

Two-dimensional flood modeling differs from 1D flood modeling in that it simulates differing flow conditions across a potential floodplain, represented as a 2D grid of cells (Nardi et al. 2008). A 2D hydrodynamic model divides the floodplain into a gridded domain (down-stream and cross-stream directions) in which complex obstacles, such as buildings, can be taken into account. Linear landscape elements are stored by combining raster (elevation) and vector (linear elements) data. Elements that may affect flood patterns are selected from a vector database. Further, 2D simulations represent an effective tool for floodplain and coastal managers to improve the prediction and management of flood hazards for those areas where the loss of channel conveyance and SLR result in large unconfined overland flow with extensive floodwave attenuation (Allsop et al. 2009). These tools can indubitably provide better predictions of flooded areas that are the inputs of geomorphological or land-cover models, which subsequently provide the inputs for metapopulation models. Thus, the combination of 2D models, which provide a spatially variable depth over the modeled domain, with geomorphological and/or land-cover models, would dramatically increase the accuracy of scenarios of landscapes and species distributions.

5.18.3.4 Models' Global Sensitivity and Uncertainty Analysis

Untangling the drivers and sources of uncertainty in mathematical models is fundamentally important to provide a reliable basis for predictions, for example, of species habitat, in the future under climatic changes. We performed a global sensitivity and uncertainty analysis (GSUA) (Saltelli et al. 2004; Campolongo et al. 2007; Munoz-Carpena et al. 2010; Chu-Agor et al. 2011a,b; Convertino et al. 2011) for the models involved in the case study of Florida (SLAMM, MaxEnt, and RAMAS) for the Snowy Plover (*C. alexandrinus nivosus*), a species highly threatened by SLR. The importance of and contribution to the uncertainty of the output has been evaluated for the intrinsic input factors of the models and the exogenous site-specific input factors. In general, the uncertainty analysis propagates the uncertainties in the model's inputs to its outputs, while sensitivity analysis determines the contribution of each input factor to the uncertainty of the outputs. Uncertainty and sensitivity were evaluated using a two-step GSUA method: the screening method proposed by Morris (1991) and a variance-based technique proposed by Sobol (1993). The Morris method provides a qualitative assessment of the importance of each input factor, while the Sobol method performs a quantitative analysis of sensitivity and uncertainty.

For the land-cover model (SLAMM), GSUA results showed that the variability in the change in area of the higher elevation wetlands (swamps and inland fresh marsh) was attributed in general to the DEM vertical error for the lower elevation range zone (0–1 m) (95–99%) and to the historic trend of SLR (1–2%) (Chu-Agor et al. 2011a). Interactions between the input factors for these wetlands were negligible. Higher-elevation wetlands showed a general decrease in area from 2060 to 2100 and from minimum to maximum SLR scenarios. This further confirmed that the most important processes involved in the fate of the coastal habitat in Eglin AFB were inundation (reduction in elevation due to SLR) and accretion/

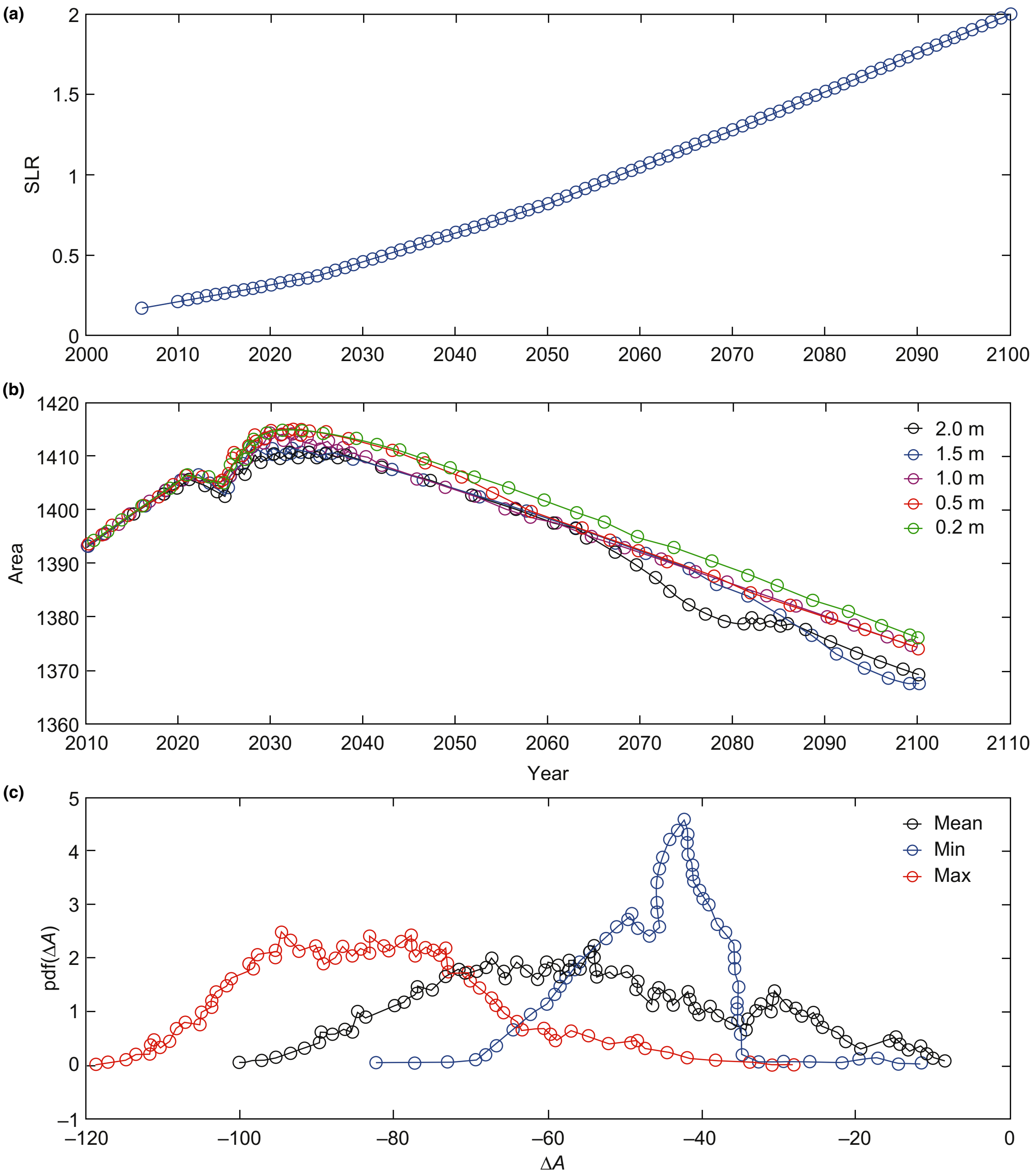

Figure 12 Sea level rise (SLR) curve and prediction of habitat for Santa Rosa Island. (a) IPCC A1B SLR curve rescaled to 2 m in year 2100 in the model simulation. (b) Changes in the area of the beach habitat (ha) consists of estuarine beach, tidal flat, and ocean beach for Santa Rosa Island at different SLR scenarios ((0.2; 2.0) m) (Linkov et al. 2010). (c) Global uncertainty analysis for the beach habitat of Santa Rosa Island (portion managed by Eglin AFB) considering the minimum, mean, and maximum SLR scenarios in the year 2100 in the model simulation (12.9, 38.7, and 69.4 cm, respectively) (Chu-Agor et al. 2011a). ΔA is the change of beach area in hectares.

sedimentation (Linkov et al. 2010; Chu-Agor et al. 2011a). For lower elevation wetlands (salt marsh, tidal flat, and beach), the variance in the output was mostly driven by varying percentages of the DEM vertical error for the lower elevation range zone (0–1 m), historic trend in SLR, salt marsh vertical accretion, and beach/tidal flat sedimentation rate, with the last two factors outweighing the others.

Figure 12(c) shows the results after global uncertainty analysis for the beach habitat of Santa Rosa Island (the portion managed by Eglin AFB), considering the minimum, mean, and maximum SLR scenario for 2100. ΔA is the predicted change in area that shows a quite broad distribution considering the uncertainty of all the input factors. To account for the variation in estimates of SLR, SLAMM simulated the habitat using minimum, average, and maximum SLR according to the IPCC A1B scenario in 2100, that is, 12.9, 38.7, and 69.4 cm, respectively.

GSUA was also applied to the habitat model (MaxEnt) (Convertino et al. 2011) and to the metapopulation model

(RAMAS) (Chu-Agor et al. 2011b) used in the Florida case study. Here, we focus our attention only on the land-cover model that produced predictions of how 'flooding' due to SLR drives the coastal wetland evolution in Florida. The GSUA revealed the dominant input factors, the complete set of scenarios for the habitat quality (from MaxEnt), and the abundance of species (from RAMAS). Thus, GSUA proved to be an extremely useful approach to evaluate the uncertainty of climate predictions – land-cover, habitat quality, and species abundance – and their most important drivers.

5.18.4 Conclusions and Perspectives

The high severity and increasing frequency of major flood events worldwide has driven flooding up the political and risk management agenda (Harvard Business School 2007). In this chapter, we compared the flooding phenomena in two very different complex coastal ecosystems as 'epitomes': Venice and the Gulf coast of Florida. These two coastal ecosystems are complex socioecological systems, and the impact of climate affects differently their natural and human components. The anthropic effect on and regulation of these ecosystems is very different; however, we focused our attention on the correlations between climatological and hydrological phenomena (flooding phenomena) and their effects on geomorphological, ecological, and socioeconomical resources. We used historical data and outputs of climatological models (ERA-40) for Venice to evaluate the drivers of flooding phenomena and the reliability of models to represent historical events. For Florida, we also run models (land-cover, habitat, and metapopulation models) to predict the future effect of SLR on coastal wetlands and shoreline-dependent birds. With our case studies we supported the idea of 'contextual vulnerability' (vs. 'outcome vulnerability') (Pielke et al. 2011) for which threats from climate need first to be considered in terms of historical observations, paleo records, and, in the worst case, sequence of events records. Estimates from the IPCC projections can then be added to the modeling part of the study to determine if climate is predicted by those models to elevate these risks. However, projections should only be performed after the historical climate evaluations are first completed. For example, the historical analysis for Venice confirmed the decreased frequency of extreme tides (Troccoli et al. 2011), and for Florida, the increased frequency of the strongest tropical cyclones (Elsner et al. 2008). In both cases, climate projections conformed to the observed historical trends; however, this may not be the case for other geographical areas or for other climatological phenomena.

The following conclusions are worth mentioning:

- Analyzing the 'high water' phenomena in Venice in 1966, 1986, 1992, and 2000, we found evidence of recurrent correlations between the MSLP gradient (Otranto–Venice), wind velocity, and meteorological tidal level. Considering the historical data in Venice, to negative peak pressure corresponds a positive peak of wind velocity and tidal level. This concurrence of events resulted in exceptional storm surge and flooding events in the city. We found that for MSLP, observed and ERA-40 values are in agreement, while for wind velocity, ERA-40 overestimates or underestimates the observed values.
- We predicted the change of the whole Gulf of Mexico Florida coastal ecosystem considering different SLR scenarios to 2100. We considered in particular the Santa Rosa Island along the north coast of Florida, which hosts 20% of the Snowy Plover population. As expected, the beach habitat posted an increase in area gained from the losses in higher elevation habitats (most probably marshes). For the first 30 years (2010–40), the beach is expected to increase. However, from 2050 forward, the area will decrease gradually until the end of the century, posting a net gain of 2.0% (54 ha). Surprisingly, different SLR projections have the same effects on the beach habitat.
- Careful data analysis is needed to disregard (or support) a priori assumptions such as negative effects of tropical cyclones on species and the increasing 'high water' phenomena in Venice due to SLR. For Florida, a positive/negative feedback has been found between the probability of presence/absence of a nesting ground and tropical cyclone/renourishment events, respectively. For Venice, recent analysis showed that regardless of the persistency of the pressure gradient Otranto–Venice, the frequency of extreme storm surge events affecting the city is going to decrease, and the frequency of extreme tides in Venice might largely remain unaltered if the projected twenty-first century climate simulations are correct (Troccoli et al. 2011). In addition, through a trend assessment based on tidal observations, Troccoli et al. (2011) found a reduction in extreme tidal levels.
- A GSUA was performed for SLAMM for the Santa Rosa Island (Eglin AFB) in Florida. The most important processes involved in the fate of the coastal habitat are different for high- and low-elevation wetlands: inundation and accretion/sedimentation for the former; elevation error, historic trend in SLR, salt marsh vertical accretion, and beach/tidal flat sedimentation rate for the latter. Simulating the IPCC A1B scenario for minimum, average, and maximum SLR, we calculated the probability of change in the beach area, considering the uncertainty of all the input factors. The distribution is quite broad; however, in all the three cases, the beach habitat is subjected to a net reduction, thus enforcing the negative effect of SLR on the Eglin coastal area. GSUA methods are thus extremely useful to assess all the possible states of ecosystems due to climate, which can aid efficient conservation actions.
- SLR studies show the importance of a correct representation of the coastal landform elevation and calculation of the water depth as a function of elevation and infrastructures. Two-dimensional flood modeling supported by vector maps, and integrated to geomorphological and land-cover models, will increase the accuracy of sea level predictions, both on urbanized and natural components of coastal ecosystems. Thus, this will increase the accuracy of predictions and possibly reduce their uncertainty.

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5.19 West Africa – Water Resources Vulnerability Using a Multidimensional Approach: Case Study of Volta Basin

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5.19.1 Introduction

Changes in climatic conditions have been evident over West Africa in the past decades. Decrease in rainfall amount led to severe droughts during the 1970s and 1980s. There has been a shift of the climatic zones in a southerly direction. Consequently, most of the Volta Basin in Burkina Faso is now located in the Sahelian and Sudano-Sahelian zones. As a consequence of instability in the rainfall pattern, many rivers have dried up, large tracts of land cover have been degraded, and the water table is drawing down.

It has been estimated that 340 km^3 of rain must fall on the catchment before runoff occurs at significant levels. This indicates that small changes in rainfall could have dramatic effects on runoff rates. For instance, a rainfall decreased by only 5% from 1936 to 1998 resulted in a runoff decrease by 14% (Andreini et al. 2000). Hydropower dams such as that in Akosombo are therefore vulnerable to even small long-term exclusions of rainfall and, by extension, all socioeconomic activities and already climatic-stressed or water-sensitive ecological systems dependent on these projects.

Extreme droughts cause severe land degradation and crop failures. High rainfall that leads to flooding can destroy crops and infrastructure. The unpredictability associated with rains could lead to high risk in agriculture investments and other water-related livelihoods.

5.19.2 The Volta River Basin: Physical Setting

The Volta River Basin is located in West Africa and covers an area of about 400 000 km^2 of the subhumid and semiarid savannah zone. The north–south extents of this transboundary basin are approximately latitude 5° 30′ N in Ghana to 14° 30′ N in Mali. The widest part stretches approximately from longitude 5° 30′ W to 2° 00′ E. The Basin meets the sea at the Gulf of Guinea in Ghana. It stretches across large proportions of Ghana (70%) and Burkina Faso (63%) and lesser proportions of Togo, Benin, Mali, and Cote d'Ivoire. The proportions of the Volta Basin located within the six West African countries are 43% in Burkina Faso; 42% in Ghana; and 15% in Togo, Benin, Cote d'Ivoire, and Mali (Figure 1).

5.19.2.1 Relief

The basin is flanked by a mountain chain on its west. From the sea and northeastwards rise the Akwapim ranges, followed by the Togo Mountain, Fazao Mountain, and Atakora ranges in Benin. The Kwahu plateau branches northwestwards after the Akosombo Gorge. The only other significant relief on the western part of the basin is the plateau of Banfora. The basin in general has a low relief, with altitudes varying between 1 and 920 m. The mean altitude of the basin is ∼257 m, with more than half the basin in the range of 200–300 m (Moniod et al. 1977).

5.19.2.2 Geology of the Basin

The geology of the main Volta Basin is dominated by the Voltaian system, which lies mainly to the west. This consists of Precambrian to Paleozoic sandstones, shales, and conglomerates. The Buem formation is another geological formation of the main Volta Basin. This series lies between the Togo series, which is to the east, and the Voltaian formation situated in the western part of the Volta Basin (Ministry of Works and Hou 1998). The Togo series and Dahomeyan and Tertiary-to-Recent formations make up the remaining geological formations of the main Volta Basin. Unlike the Voltaian system, the Buem series comprise calcareous, argillaceous, sandy, and ferruginous shales, sandstones, arkose, greywacke, tuffs, and jaspers. The Togo series on the other hand consists of alternating arenaceous and argillaceous sediments and lie toward the eastern and southern parts of the main Volta Basin. The Dahomeyan system, which consists of mainly metamorphic rocks, including hornblende and biotite, gneisses, magmatites, granulites, and schist, is generally found at the southern part of the main Volta Basin.

The Voltaian system, the Buem formation, and the Togo series constitute the major geological formations of the Oti River Basin. The White Volta Basin on the other hand has the Birimian system and the Tarkwaian formation, with the Birimian system consisting of metamorphosed lavae, pyroclastic rocks, phyllites, schists, tuffs, and greywackes. Associated with the Tarkwaian formation are quartzites, phyllites, grits, conglomerates, and schists (Figure 2).

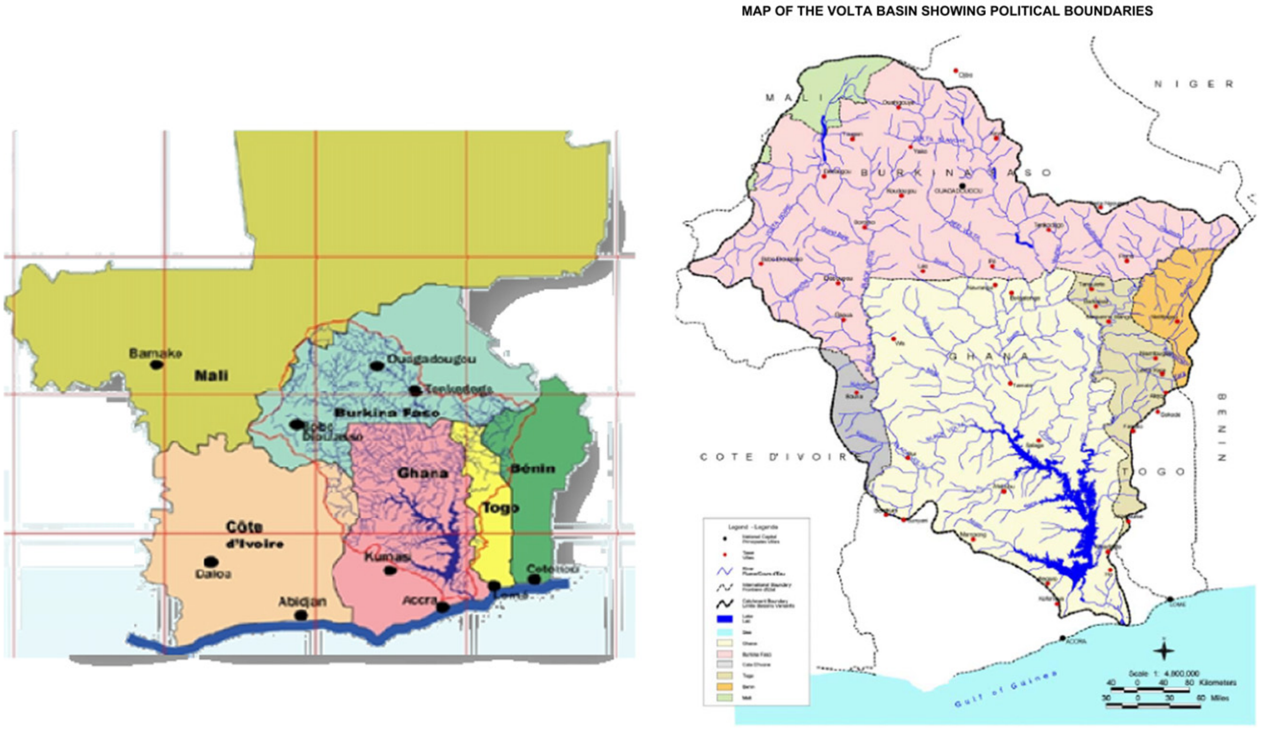

MAP OF THE VOLTA BASIN SHOWING POLITICAL BOUNDARIES
Bamako
Mali
Ouagadougou
Tenkodogo
Burkina Faso
Bobo Dioulasso
Ghana
Bénin
Togo
Côte d'Ivoire
Daloa
Kumasi
Abidjan
Accra
Lomé
Cotonou
MALI
NIGER
BURKINA FASO
GHANA
COTE D'IVOIR
TOGO
BENIN
OUAGADOUGOU
ACCRA
LOME
Gulf of Guinea
Scale 1: 4,800,000
Kilometers
Miles
Legend - Legende

Figure 1 The Volta Basin showing political boundries and important tributaries. Source: Andah and Gichuki 2003.

5.19.2.3 Drainage Network and Sub-Basins

Surface water is received from both outside and within the country. Approximately 54% of the flows of the tributaries originate from outside the country. However, in 1970, it was estimated to be around 70%. The apparent reduced contribution may be due to the reduction in rainfall magnitudes in the Sahel since the 1970s (Nicholson 1983). The network of the Volta River System within the territory of Ghana covers about 70% of the total land surface of Ghana. The main subcatchments are the Black Volta, White Volta, and Main/Lower Volta, and Oti and Daka Rivers (Biswas and Obeng).

5.19.2.3.1 The White Volta Basin

The White Volta Basin covers an area of about 49 210 km^2 in Ghana, representing 46% of its total catchment area of 10 741 km^2. The Maorago subcatchment of the White Volta has a total area of 1608 km^2 and stretches across Ghana and Togo. The Tamne subcatchment of the White Volta lies entirely in Ghana. The average annual runoff from the White Volta is about 272 m^3 s^{-1}. The White Volta contributes about 20% of the annual total flows to the Volta Lake.

5.19.2.3.2 The Black Volta Basin

The Black Volta has a total transboundary catchment area of 142 056 km^2. Only 33 302 km^2 (23.5%) of the catchment area is located in Ghana, primarily northwestern Ghana. The annual runoff from the Black Volta Basin is about 243 m^3 s^{-1}. It contributes about 18% of the annual total flows to the Volta Lake.

5.19.2.3.3 The Lower Volta Basin

The lower basin is located below the confluence of the Black Volta and the White Volta Rivers, excluding the Oti River drainage area. The surface water resources consist of flows from outside and within Ghana. The basin covers a total area of about 68 588 km^2, with 50 432 km^2 located in Ghana. The natural total mean runoff from the basin is estimated at 1160 m^3 s^{-1}.

5.19.2.3.4 Oti Basin

The Oti River Basin has an area of 16 801 km^2 in northeastern Ghana, with the remaining located in Togo. The discharge from the Oti Basin is about 10–1270 m^3 s^{-1}. The annual flow from the Oti River Basin contributes about 25% of the annual total flows to the Volta Lake due to the steep topography and the relatively high rainfall within the basin.

5.19.2.3.5 Daka Basin

The Daka Basin covers an area of 7424 km^2 and is located almost entirely in the eastern part of northern Ghana. The annual rainfall in the basin varies between 1120 and 1340 mm. Most of the biophysical characteristics found in the basin are similar to those of the Oti River Basin.

5.19.2.4 Rainfall

Climatic conditions are controlled by two air masses: the northeast trade winds (harmattan) and the southwest trade winds (monsoon). The dry northeast trade winds originate from the interior of the continent, whereas the southwest

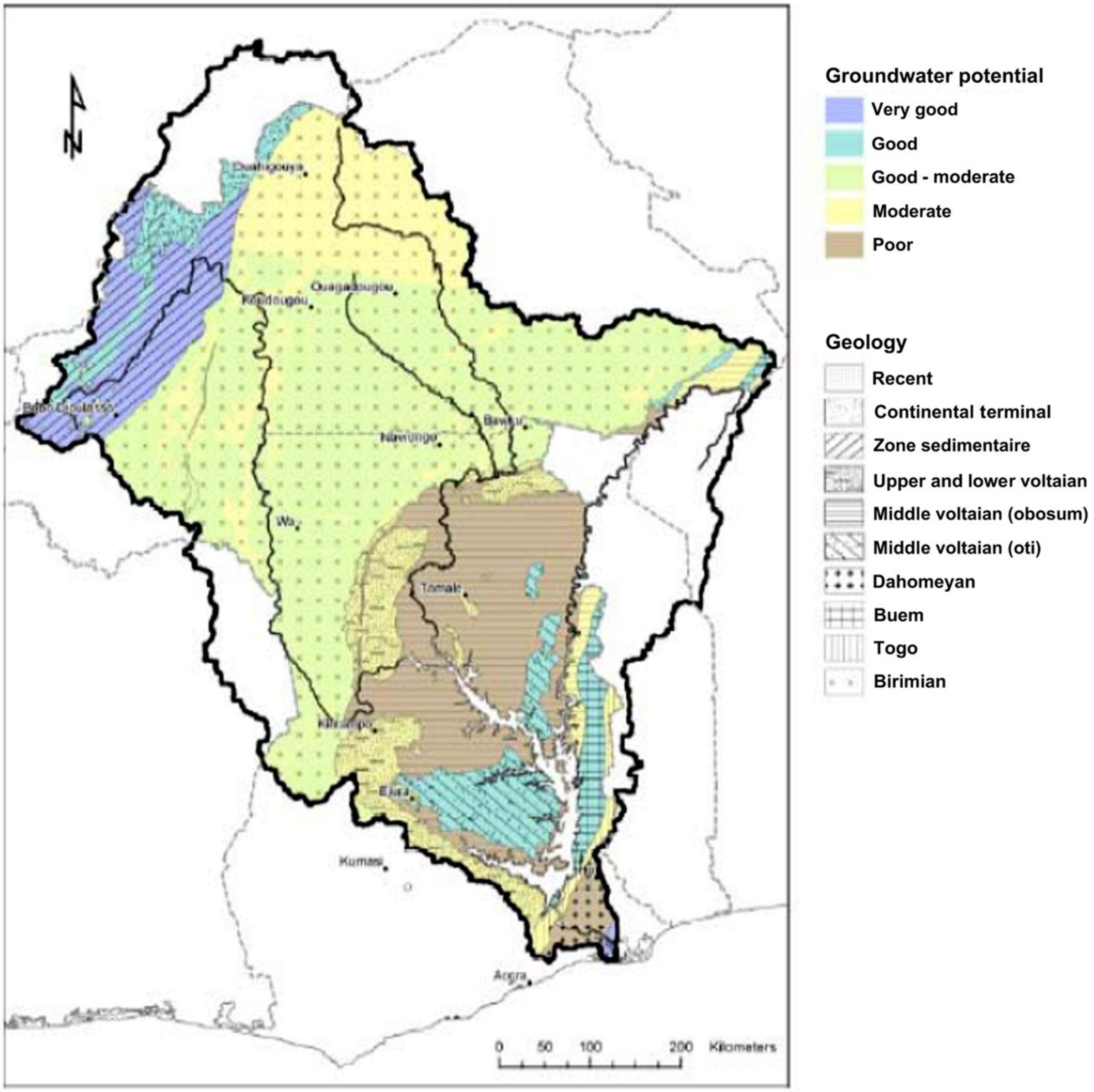

N
Ouahigouya
Ouagadougou
Koudougou
Bobo-Dioulasso
Bawku
Nawungo
Wa
Tamale
Kintampo
Ejura
Kumasi
Accra
0 50 100 200 Kilometers
Groundwater potential
Very good
Good
Good - moderate
Moderate
Poor
Geology
Recent
Continental terminal
Zone sedimentaire
Upper and lower voltaian
Middle voltaian (obosum)
Middle voltaian (oti)
Dahomeyan
Buem
Togo
Birimian

Figure 2 Groundwater potential and geology of Volta Basin.

trade winds are moist since they blow over the seas. The interphase of these two air masses, the intertropical convergence zone (ITCZ) is associated with a considerable amount of rainfall. The ITCZ moves northwards and southwards across the basin from about March to October, when rainfall is received in the region. More detailed information is given in Section 5.19.5.

Three types of climatic zones are identified in the region: the humid south with two distinct rainy seasons, the tropical transition zone with two seasons of rainfall – very close to each other, and the tropical climate north of latitude 9° N. Average annual rainfall varies across the basin from approximately 1600 mm in the southeastern section of the basin in Ghana to about 360 mm in the northern part of Burkina Faso. The rainfall days decreases in a south–north direction. For instance, in the Sahelian zone the rainy season lasts for about 3 months, whereas there are about 6–7 months of rainfall days in the southern part of the Sudan zone. Dominant winds blow east–west from January to March, which is the harmattan season. Rainfall reduction has been evident since the 1970s (Opoku-Ankomah 2000). Some areas that used to have bimodal type of rainfall have only one mode, as

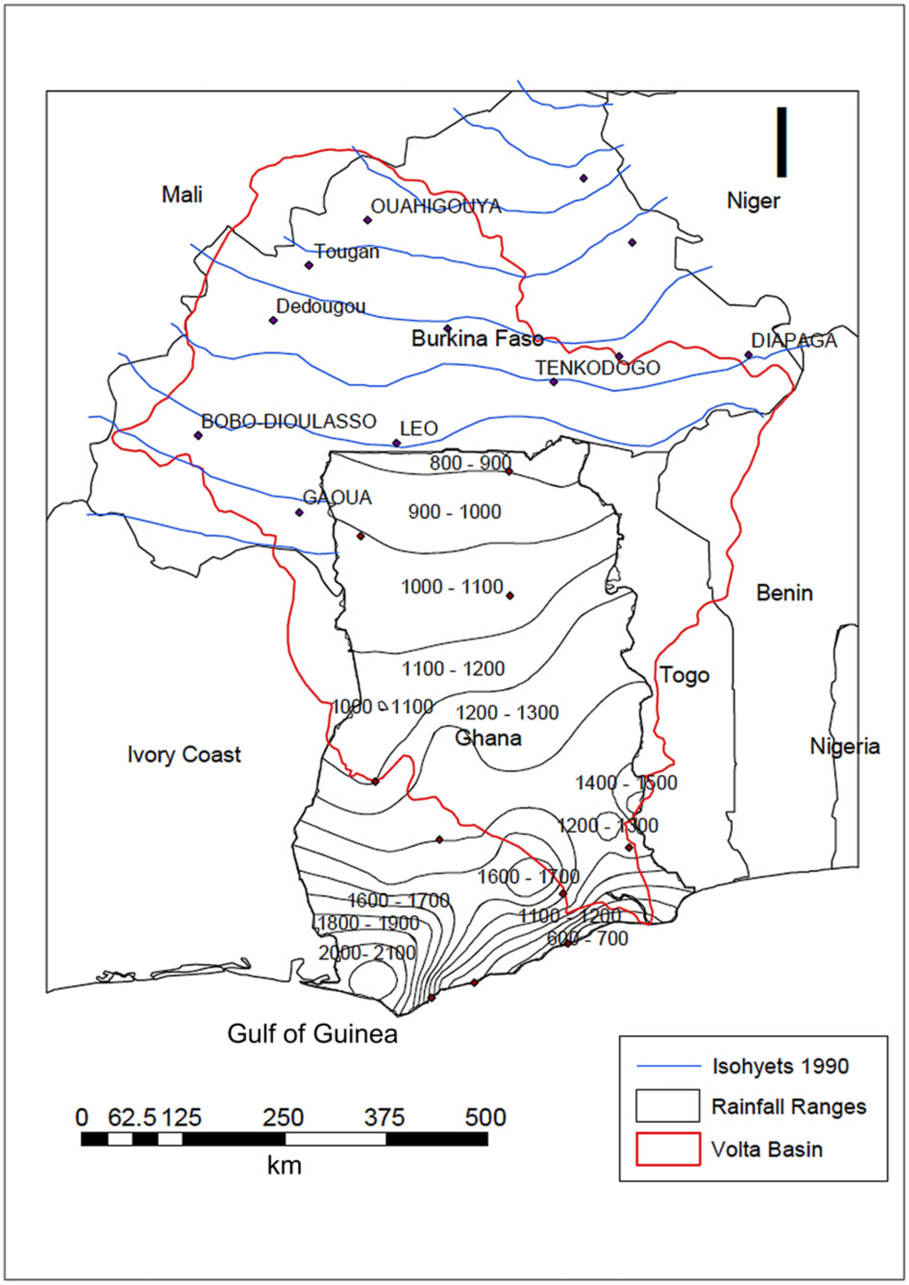

Mali
OUAHIGOUYA
Niger
Tougan
Dedougou
Burkina Faso
DIAPAGA
TENKODOGO
BOBO-DIOULASSO
LEO
800 - 900
GAOUA
900 - 1000
1000 - 1100
Benin
1100 - 1200
Togo
1000 - 1100
1200 - 1300
Ghana
Ivory Coast
Nigeria
1400 - 1500
1200 - 1300
1600 - 1700
1600 - 1700
1800 - 1900
1100 - 1200
600 - 700
2000- 2100
Gulf of Guinea
Isohyets 1990
Rainfall Ranges
Volta Basin
0 62.5 125 250 375 500
km

Figure 3 Distribution of rainfall in Volta Basin in 1990.

the second minor season has become very weak or nonexistent (Figure 3).

5.19.2.5 Temperature and Humidity

The annual mean temperatures in the basin vary from about 27–30 °C. Daily temperatures can be as high as 32–44 °C and as low as 15 °C nocturnally. Humidity varies between 6 and 83% depending on the season and the location. Temperatures are higher in the upstream than downstream.

In Ghana, the mean air temperature never falls below 24 °C because of its proximity to the equator. The hottest month of the year is March–April and the coolest is August. The southern section of the country is more humid than the north. In the coastal area of Ghana, the relative humidities are 95–100% in the morning and about 75% in the afternoon. In the north, values can be as low as 20–30% during the harmattan period and 70–80% during the rainy period. The first cool period occurs in December–February, with average maximum temperatures varying between 33 and 35 °C in January and average minimum temperatures in the order of 14 (north), 17 (center), and 19 °C (south). The average maximum and minimum temperatures during this cool period are subject to extreme variations because of the irregularity of the rains (Figure 4).

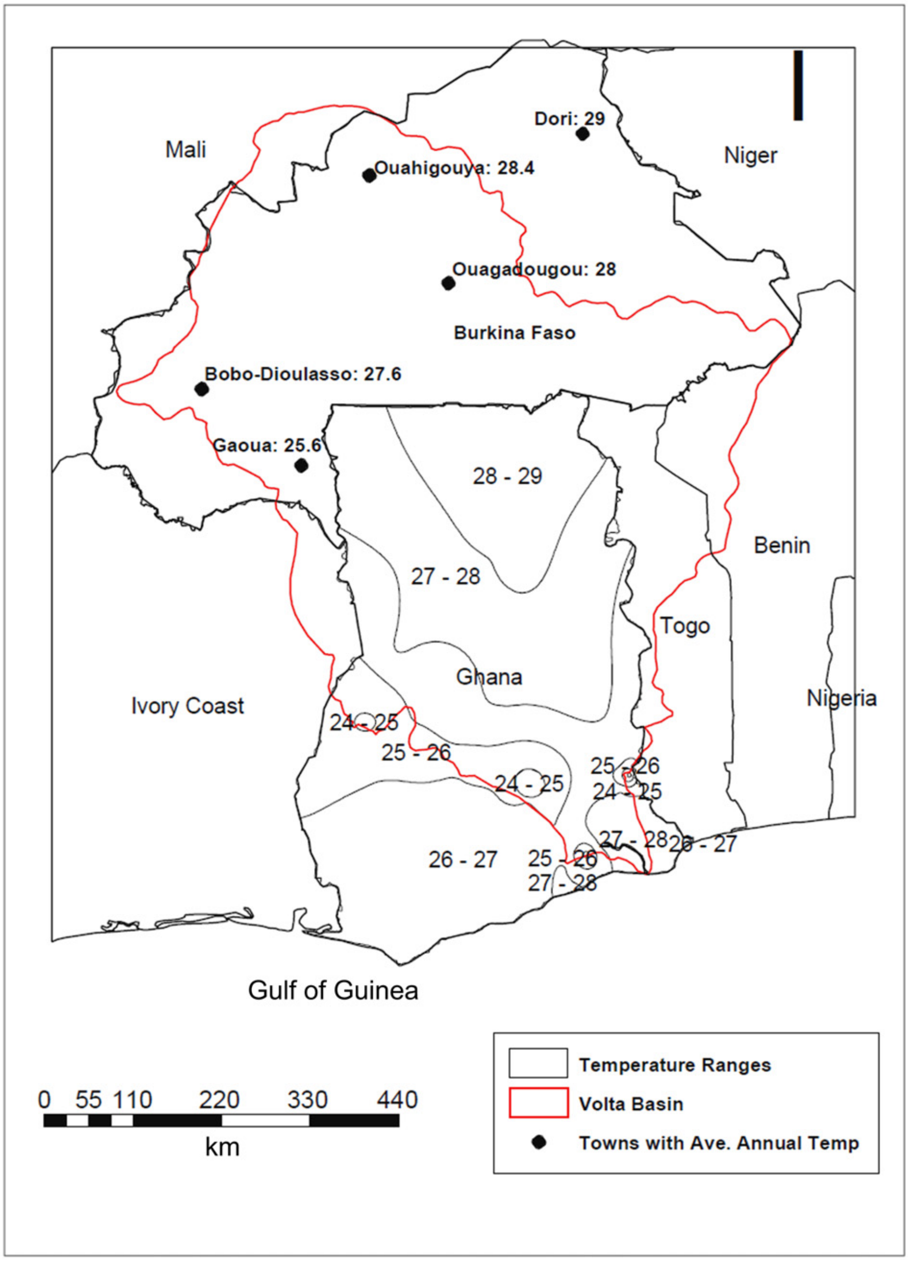

Mali
Dori: 29
Niger
Ouahigouya: 28.4
Ouagadougou: 28
Burkina Faso
Bobo-Dioulasso: 27.6
Gaoua: 25.6
28 - 29
27 - 28
Benin
Togo
Ghana
Ivory Coast
Nigeria
24 - 25
25 - 26
24 - 25
25 - 26
24 - 25
27 - 28
26 - 27
26 - 27
25 - 26
27 - 28
Gulf of Guinea
0 55 110 220 330 440
km
Temperature Ranges
Volta Basin
Towns with Ave. Annual Temp

Figure 4 Spatial distribution of temperature in Volta Basin.

5.19.2.6 Evaporation and Evapotranspiration

Evaporation in the basin is relatively high, especially in the Sahelian zone. In Burkina Faso, the lowest record is about 1900 mm per annum. In the Volta Basin of Ghana, potential evapotranspiration varies from a minimum of 1450 mm per annum in the Black Volta subbasin to a maximum of 1968 mm per annum in the White Volta subbasin. Panevaporation is the same (2540 mm per annum) in all the sub-basins except the lower basin. In Burkina Faso, average annual panevaporation values are generally very high and progressively increase from south to north (Figures 5 and 6).

5.19.3 Surface Water Sources and Quality in the Volta System

Although some historical data was available for all the rivers in the Volta Basin, these varied greatly in terms of period and time when they were studied. The mean results of the physico-chemical analysis of samples collected from several stations give an indication of the quality of the river systems. Sampling stations were located on tributaries of the Volta as well as the main lake; the data is therefore fairly representative of the quality of the entire lake.

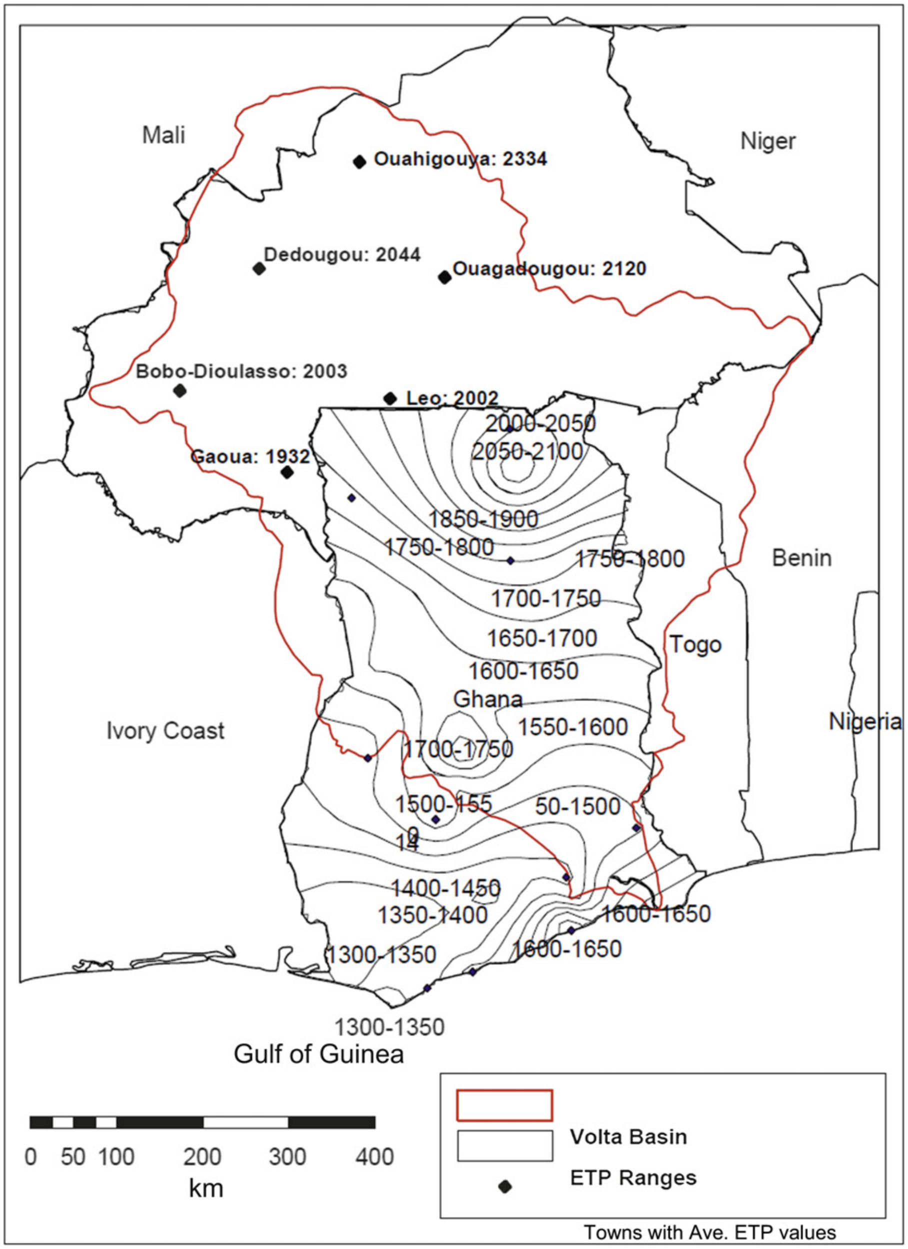

Mali
Niger
Ouahigouya: 2334
Dedougou: 2044
Ouagadougou: 2120
Bobo-Dioulasso: 2003
Leo: 2002
Gaoua: 1932
2000-2050
2050-2100
1850-1900
1750-1800
1750-1800
1700-1750
1650-1700
1600-1650
Ghana
1550-1600
1700-1750
1500-155
0
14
50-1500
1400-1450
1350-1400
1600-1650
1300-1350
1600-1650
1300-1350
Benin
Togo
Nigeria
Ivory Coast
Gulf of Guinea
0 50 100 200 300 400
km
Volta Basin
ETP Ranges
Towns with Ave. ETP values

Figure 5 Towns with average ETP values.

5.19.3.1 Thermal Changes in the Volta Lake

Significant thermal changes were observed in the main Volta Lake, near Akosombo, during the early stages of filling, between 1964 and 1966. As the lake filled, Biswas (1968) described appreciable differences between the surface and the bottom. The mean temperatures for all the data collected were 29.09 °C for the surface and 26.97 °C for the bottom. Major changes in the surface and bottom temperatures are presented in Table 1. Temperatures in both locations experienced considerable undulating rises and falls over the period of study. The surface temperature decreased significantly from June to August 1964. It then increased gradually from September 1964 and peaked in May 1965; thereafter, there was a rapid decrease, reaching a low point in August 1965. This was followed by a general rise, resulting in a peak in April 1966.

The bottom temperature also decreased significantly from June to August 1964. It continued decreasing and reached its lowest in October 1964, then rose gradually until July 1965, and maintained an average of 27.24 until March 1966. Five years later (1971), intensive studies carried out by the Government of Ghana showed that both the surface temperature (29 °C) and the bottom temperature (27 °C) did not vary much.

5.19.3.2 Other Physicochemical Parameters

Early studies carried out by Entz (1968) between 1965 and 1966 showed that the lake was chemically oligotrophic, with

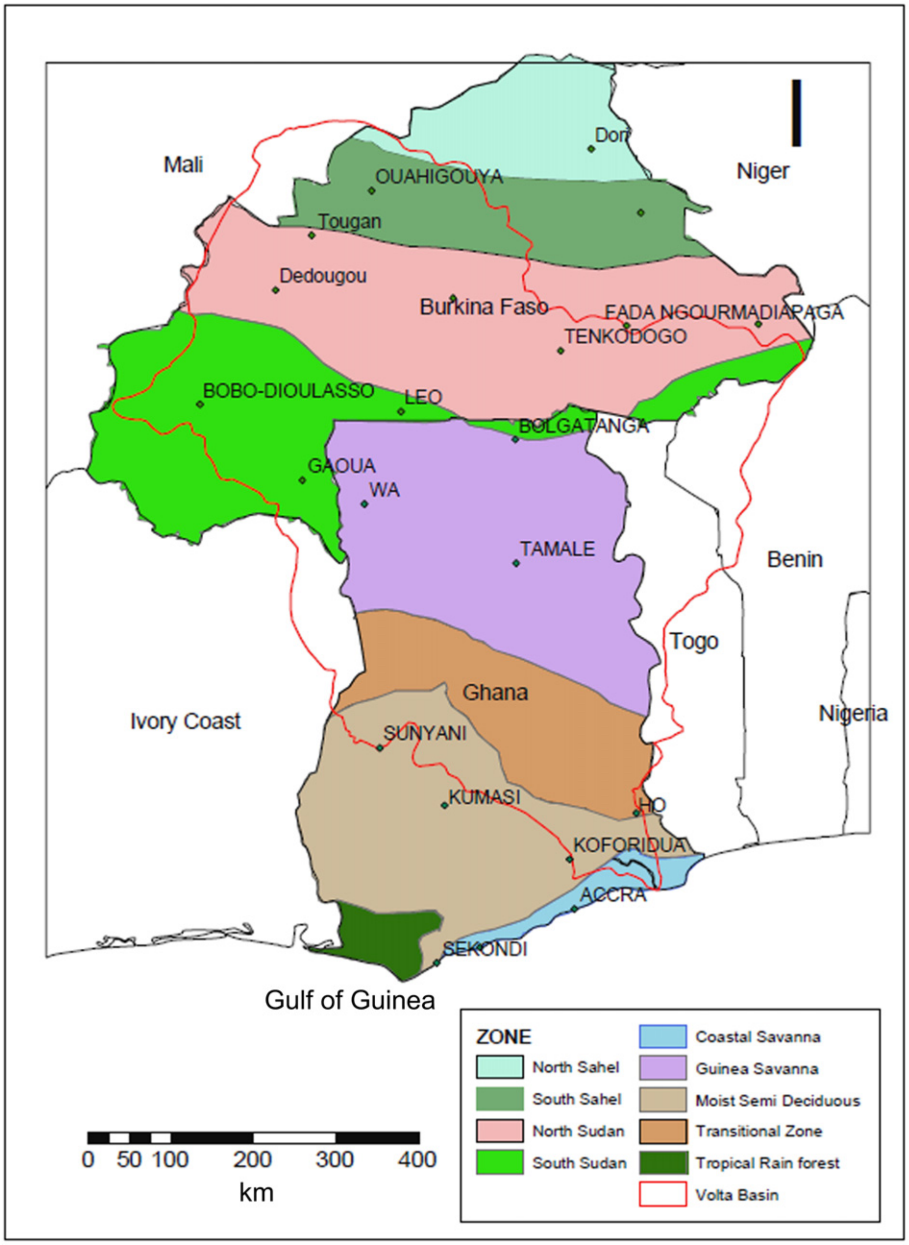

Mali
Niger
Dori
OUAHIGOUYA
Tougan
Dedougou
Burkina Faso
FADA NGOURMA
DIAPAGA
TENKODOGO
BOBO-DIOULASSO
LEO
BOLGATANGA
GAOUA
WA
TAMALE
Benin
Togo
Ghana
Ivory Coast
Nigeria
SUNYANI
KUMASI
HO
KOFORIDUA
ACCRA
SEKONDI
Gulf of Guinea
0 50 100 200 300 400
km
ZONE
North Sahel
South Sahel
North Sudan
South Sudan
Coastal Savanna
Guinea Savanna
Moist Semi Deciduous
Transitional Zone
Tropical Rain forest
Volta Basin

Figure 6 Map showing the agroecological zones of Ghana and Burkina Faso.

low levels of parameters such as HCO_3^-, Ca^{2+}, Mg^{2+}, Na^+, total Fe, NO_2^- and PO_4^-, among others.

Iron (II) and chloride were, however, high in some tributaries like the Dayi. Within this period, no remarkable limnological changes took place within the upper 5-m layer of the Volta Lake. More extensive studies carried out later by Andah et al. (2003) on ADAPT (adaptations strategies to changing environments in the Volta Basin) Volta project for these parameters (Table 2) indicated slightly elevated levels over those recorded by Entz (1968). Andah et al. between 1976 and 1978 recorded physicochemical measurements that included transparency (which varied from 400 cm in the main lake to 30 cm in the north during the flood period), pH, alkalinity, phosphate, nitrate, ammonia, iron, silica, calcium, magnesium, potassium, sodium, and hydrogen sulphide.

Nutrient content of the Volta Lake is low compared to other tropical lakes, but high concentrations occurred during flood, under conditions of strong mixing. The Afram arm recorded the least nutrient content as compared to the other tributaries; for instance, ammonium concentration ranged from 0.02 to 0.04 mg l^{-1} at all levels except at the bottoms, where sometimes values as high as 5.20 mg l^{-1} were registered. The nitrite form was not detected at all, except, occasionally at the very bottom where values scarcely reached 0.01 mg l^{-1}. The nitrate form on the other hand was always present but in low values ranging between 0.01 and 0.03 mg l^{-1} (Obeng-Asamoah 1977).

Table 1 Monthly mean of surface and bottom temperatures (°C) of Volta Lake at Akosombo (Ajena)

Month	*Surface: 1964–65*	*Surface: 1965–66*	*Bottom: 1964–65*	*Bottom: 1965–66*
June	30.00	29.45	29.50	26.80
July	28.12	28.60	27.72	27.26
August	27.25	27.95	26.75	27.15
September	27.60	28.30	26.25	27.15
October	27.84	29.28	25.60	27.20
November	28.00	30.15	25.90	27.05
December	28.70	29.56	26.45	27.00
January	28.35	28.90	26.88	27.00
February	29.20	28.95	27.20	27.00
March	29.20	30.30	26.90	27.00
April	30.14	30.44	26.96	26.96
May	30.83	30.37	26.90	26.80
June	–	29.82	–	26.88

Source: Biswas, E. R. I. 1968: Thermal changes in the Volta Lake in Ajena. *Man-Made Lakes.* L. E. Obeng, Ed., Ghana Academy of Sciences, 103–109.

The pH ranged in the northern sections of the lake between 6.8 and 7.4 at the surface and stabilized at 6.7 at the bottom. In the south, the pH on the surface ranged from 7.8 to 8.5. The inflowing tributaries were observed to sometimes have higher pH values. Free carbon dioxide followed the normal pattern, mostly increasing toward the bottom following the decrease of oxygen. In the thermocline or whenever the dissolved oxygen (DO) content drops to zero, an increase in free carbon dioxide followed.

Marked differences in total alkalinity of water were found between the upper and lower reaches of the Volta River before the dam was built. This also applied to the smaller and larger tributaries. After the dam was built, the differences were nearly equalized, and there was hardly any change from north to south. The content ranged between 19 and 41 mg $CaCO_3$ in the open lake, was 50 mg l^{-1} in the Sene River, and was up to 60 mg l^{-1} in the Afram arm. In general, the alkalinity of the Volta Lake was very low. Iron was mostly detected in the surface water layers in the north. In the south it was found only in the hypolimnion but in higher concentrations. The distribution of orthophosphates in the lake was similar to that of iron. Phosphates were recorded at all depths in relatively high concentrations (up to 0.5 mg l^{-1}) in the north, where it is possibly brought in by the Black and White Voltas.

In all other parts of the lake, orthophosphate was sometimes not detectable in the epilimnion, especially after long periods of stagnation. In all probability the lack of phosphorus prevented an improvement of primary production in the main lake. The same pattern existed for nitrate-nitrogen. In the northern regions as well as the upper parts of the tributaries, the amounts were quite high and had the tendency to decrease toward the south. However, as soon as a water bloom of phytoplankton appears, this nutrient depletes almost entirely in the surface layers. Nitrate-nitrogen was not necessarily a limiting factor in phytoplankton production in the lake, as it might be in other lakes. Ammonia was mostly present in the hypolimnion where it accumulated during the stagnation period, similar to iron and phosphates.

Silica was always available in sufficient quantities, between 12 and 25 mg l^{-1} SiO_3 in the main lake, and up to 27 mg l^{-1} in the upper Afram for diatom production. Calcium and magnesium were uniform in vertical as well as in horizontal distributions and ranged mostly under 10 mg l^{-1} Ca and 5 mg l^{-1} Mg. The same can be said for potassium and sodium, which had low values. Conductivity ranged from 63 μS cm^{-1} in the north up to 172 μS cm^{-1} at Kete Krachi. The differences between the surface and the bottom were very little. A study by Amoah and Koranteng (Amoah and Koranteng 2008) from 1996 to 2006 in the lower Volta indicates that parameters such as surface temperature, pH, conductivity, and nitrate-nitrogen did not change much. However, there has been a remarkable increase in the levels of other parameters such as total hardness and chloride (Table 3). Similarly, a recent study (Abdul-Razak et al. 2009) on the Oti River indicates deterioration in parameters such as pH, and nitrate-nitrogen, DO, and

Table 2 Summary of water quality in Oti, White, Black, and Lower Volta

	Oti River at Sabra (Nov. 76 to Feb. 78)		*White Volta at Daboya (Aug. 77 to Feb. 78)*		*Black Volta at Bamboi (Aug. 77 to Feb. 78)*		*Lower Volta at Amedeka (Apr. 77 to Mar. 78)*	
Parameter	Mean	Std deviation	Mean	Std deviation	Mean	Std deviation	Mean	Std deviation
pH	6.9	0.5	6.9	0.4	7.0	0.5	7.1	0.3
Conductivity	280	213	194	156	201	154	520	245
Dissolved oxygen	9.9	2.4	10.6	3.8	11.2	3.1	8.0	2.0
Biological oxygen demand	2.7	1.3	1.05	0.5	3.8	2.3	2.8	2.2
Alkalinity	35.3	11.5	42.6	16.5	53.8	23.6	44.8	6.4
Chloride	5.4	2.8	13.6	8.6	7.0	0.8	4.6	2.5
Calcium	4.8	2.0	6.8	2.0	10.1	2.9	5.3	1.4
T hardness	22.9	10.8	30.4	2.8	44.1	18.6	17.4	7.3
Magnesium	4.3	2.2	5.8	0.8	8.3	4.1	2.5	1.9
Ammonia-N	1.0	1.5	1.6	2.9	1.5	2.4	0.4	0.5
Phosphate	0.9	0.4	0.7	1.0	0.6	1.9	0.2	0.3
Nitrate	0.2	0.1	0.5	0.6	0.2	0.1	6.6	10.9
Nitrite	0.08	0.02	0.06	0.08	0.1	0.1	0.6	1.3
Sulfate	5.7	6.6	8.9	10.7	7.0	8.4	1.2	0.8

Source: Andah, W. E. I., N. van de Giesen, and C. A. Biney, *Water, Climate, Food, and Environment in the Volta Basin.* 41 pp. [Available online at http://www.weap21.org/downloads/ADAPTVolta.pdf.]

Table 3 Range of parameters recorded in the Lower Volta from 1996–2006

Temperature (°C)	*pH*	*Conductivity (μS cm^{-1})*	*Hardness (mg l^{-1})*	*Nitrate (mg l^{-1})*	*Chloride (mg l^{-1})*
27–29.8	7–7.9	105–286.6	60.5–140.2	0.1–0.5	26–275

Source: Amoah, C. M., and S. S. Koranteng, 2008: Sources and quality of drinking water of the inhabitants in the Lower Volta Basin of Ghana. *New Developments on Health, Agricultural Resources and Socio-Economic Activities in the Volta Basin, Ghana*, C. M. Amoah, S. G. K. Adiku, and E. O. Owusu, Eds., Volta Basin Research Project, 43–54.

bacteriological content, while other physicochemical parameters did not vary much.

5.19.3.3 Bacteriological Quality

Data on the bacteriological quality of Volta Lake covering the period of filling is virtually absent. Initial studies during the formation period carried out by Biswas (1968), 1 km from the dam site, showed that bacteria counts were higher at the surface and decreased with depth (Table 4). However, post-impoundment studies carried out by Amoah (1999) at 10 years interval, 1977 and 1987, both within the main lake around Akosombo and along the Afram tributary showed increase in bacterial population with depth in contrast to Biswas (1968); the deeper parts, 20 m and below, supported higher counts, with two peaks coinciding with the major and minor rainy seasons.

5.19.4 Groundwater Sources in the Volta Basin of Ghana

5.19.4.1 Hydrogeology

Three major hydrogeologic systems govern groundwater resource availability in Ghana. These include the basement complex composed mainly of Precambrian crystalline igneous and metamorphic rocks and the Paleozoic consolidated sedimentary formations. The basement complex constitutes about 54% of the geological formation of the country. It is made up of a wide variety of Precambrian igneous and metamorphic rocks. Generally, the basement complex consists of gneiss, phyllite, schist, mihnatite, granitegneiss, and quartzite. On the basis of geology and groundwater conditions, this can further be divided into subregions. These subregions include the metamorphosed and folded rocks of the Birimian system, the Dahomeyan system, the Tarkwaian system, the Togo series, and the Buem formation. Groundwater occurrence in this complex is associated with secondary porosity resulting from jointing, shearing, fracturing, and weathering. This is on account of the fact that the underlying rocks of the basin are essentially impermeable and have very little or no inherent porosity.

Table 4 Vertical distribution of heterotrophic bacteria at Akosombo and Afram arm

	Akosombo			*Afram arm*		
	Total number of colonies			*Total number of colonies*		
Depth (m)	*1967*[a]	*1977*[b]	*1987*[b]	*1967*[a]	*1977*[b]	*1987*[b]
0–1	611	63	83	180	80	84
5	614	149	112	171	131	207
10	354	231	167	170	269	236
15	–	204	197	–	248	244
20	–	233	244	157	261	271
25	239	328	288	360	273	390
46–65	321	–	432	–	–	–

[a] Biswas, E. R. I., 1968: Thermal changes in the Volta Lake in Ajena. *Man–Made Lakes.* L. E. Obeng, Ed., Ghana Academy of Sciences, 103–109.

[b] Amoah, C. M., 1999: Overview of microbiological studies on the Volta Lake. *The Sustainable Integrated Development of the Volta Basin in Ghana.* C. Gordon and J. K. Amatekpor, Eds., Volta Basin Research Project, 33–3.

The second geological formation associated with groundwater resources in Ghana is the Paleozoic consolidated sedimentary formations. Locally referred to as the Voltaian formation it underlies about 45% of the country and consists mainly of sandstone, shale, arkose, mudstone, sandy and pebbly beds, and limestone. This formation is further subdivided into Upper Voltaian, Middle Voltaian, and Lower Voltaian on the basis of lithology and field relationships. The Upper Voltaian formation consists of massive sandstone and thin-bedded sandstone, with the Middle Voltaian formations having the Obusum and Oti Beds.

Mesozoic and Cenozoic sediments make up the remaining 1% of the rock formation and are found in two coastal provinces. These are the Block-Fault and the Coastal Plain Provinces and the Alluvial Province. The coastal Block-Fault Province consists of a narrow discontinuous belt of Devonian and Jurassic sedimentary rocks that have been broken into numerous fault blocks and are transacted by minor intrusion. The Coastal Plain hydrogeologic province on the other hand is underlain by semiconsolidated to unconsolidated sediments. These range from Cretaceous to Holocene in age and could be found on the southeastern part of Ghana, in a relatively small isolated area in the extreme south of the western part of the country. Narrow bands of alluvium of Quaternary age, occurring mainly adjacent to the Volta River and its major tributaries and in the Volta delta form the majority of the alluvial hydrogeologic province (Moniod et al. 1977; Dapaah-Siakwan and Gyau-Boakye 2000; Acheampong and Hess 1998).

5.19.4.2 Aquifers in Ghana

Groundwater flow patterns and recharge systems in Ghana have generally not been very easy to gauge properly, because of the complexity of the terrain (Community Water and Sanitation Agency 2001). Generally, the basement complex and the Voltaian formation, which underlie about 99% of the country, are impermeable and, thus, have no inherent porosity. Groundwater occurrence in these formations is therefore associated with the development of secondary porosity resulting from jointing, shearing, fracturing, and weathering. Two main types of aquifers are therefore identified, namely, weathered zone aquifers and fractured zone aquifers (Acquah 2002).

The weathered zone aquifers occur mostly at the base section of the thick weathered layer and vary from outcrops to about 100 m depth. It is thickest in the wet forested southwestern part of the country where it reaches an average thickness of about 60 m depth. The weathered layer is very thin at the semiarid zone of the extreme northeast where the average thickness is about 10 m. The fractured zone aquifers on the other hand are discontinuous and limited in area. Groundwater occurs mostly under semiconfined or leaky conditions because of the sandy clay nature of the weathered overburden, and yields rarely exceed 6 $m^3 h^{-1}$.

Aquifers occurring in the remaining 1% of the formations in Ghana are confined mainly to the extreme southeastern and western parts of the country and are associated with the Cenozoic and Mesozoic sediment formations. One aquifer occurs in the resent sand, which is very close to the coast. The aquifer, which is unconfined, is located at a depth of between 2 and 4 m and contains fresh meteoric water. An intermediate aquifer that is either confined or semiconfined occurs mainly in the red continental deposits of sandy clay and gravel. This aquifer varies in depth from 6 to 120 m and contains mostly saline water. A third type of aquifer could be located at depths of between 120 and 300 . This type of aquifer is often referred to as limestone aquifer. With an average yield of about 148 $m^3 h^{-1}$, the groundwater in this aquifer is fresh and occurs under artesian conditions.

Owing to lithological variables and structural complexes of the rocks, yields from boreholes in the various geological formations are variable. Studies conducted by the Water Resources Research Institute in Ghana on borehole yields indicate average yields that vary widely, ranging from about 3.0 to 12.7 $m^3 h^{-1}$ in the basement complex, about 8.5 $m^3 h^{-1}$ in the Voltaian formation, and in a range of 4.0 to about 11.7 $m^3 h^{-1}$ within the Mesozoic and Cenozoic formations (Acheampong and Hess 1998).

Information on groundwater recharge in Ghana is very scanty, although recharge of most of the aquifer systems in Ghana is thought to be by direct infiltration of precipitation through fault zones and fractures along the highland fronts and also through the sandy portions of the weathered zone. Substantial amounts of recharge are also thought to occur through seepage from ephemeral stream channels during the rainy seasons. In addition, some indirect recharge mainly occurs in the lower rainfall, low-relief, and low-permeability areas, especially, when runoff from watershed outside the areas or a particular storm event is of sufficient magnitude to cause runoff. This is made possible when drainage courses or streams that act as conduits for the overland flows allow a greater part of the runoff to infiltrate through their beds to the groundwater table on account of their generally weak fissured zones.

Studies conducted by some researchers in Ghana over the years indicate that the quality of groundwater in Ghana is generally good for multipurpose use (Kortatsi 1994; Moniod et al. 1977; Andah 1993; FAO 1996).

For both human consumption and irrigation, groundwater is globally regarded as a very important resource. The occurrence of groundwater in Ghana is associated with the three main geological formations of the Volta Basin. These include the basement complex made up of crystalline igneous and metamorphic rocks.

5.19.5 Agroecological Zones in the Volta Basin of Ghana

An agroecological zone is a land resource mapping unit defined in terms of climate, landform and soils, and/or land cover, which has a specific range of potentials and constraints for land use (Barry et al. 2005).

In Ghana, six major agroecological zones are recognized. These zones are defined by climatic and edaphic factors and reflected in the distinctiveness of the associated natural vegetation. There is a vicious gradation from forest to grassland as one moves from the lower latitudes in the south to the higher ones in the north. The zones consist of the high rainforest zone, the semideciduous forest (SDF) zone, the forest–savanna transitional zone, the guinea savanna zone, the Sudan savanna zone, and the coastal savanna zone. There are considerable variations between successive rainy seasons in terms of the onset, duration, and amount of fall. Rainfall within the agroecological zones is generally accompanied by high intensities and energy loads and is therefore erosive. Generally, alluvia soils (Fluvisols) and eroded and shallow soils (Leptosols) are found in all the agroecological zones (Obuobie and Barry 2010; Amatekpor 1997).

The Volta Basin, which occupies approximately two-thirds of Ghana, transcends five of the six major zones, excluding the high rainforest zone, which is located at the extreme southwestern corner of the country. In addition, mangrove swamps are found, albeit in patches along the entire Volta Basin coastline and beyond (Gyasi and Enu-Kwesi 1997). The basin, therefore, encompasses a wide diversity of floral and faunal species in line with the variety of ecological zones. The zones have, however, undergone tremendous changes as a result of anthropogenic forces induced by population and production pressures (EPA 2002). Pristine vegetation is almost absent apart from a few protected areas, steep slopes, and river courses within the basin.

5.19.5.1 Coastal Savanna Zone

The costal savanna zone in Ghana covers an estimated area of 4500 km^2. Rainfall in the zone is bimodal, varying between 600 and 900 mm, with an annual average of about 810 mm. The major rainy season occurs from March to mid-July, with a peak fall in June. The minor rainy season starts in early September and ends at the beginning of November. The major dry season occurs between mid-November and end of February (Gordon et al. 2003). The mean annual maximum and minimum temperatures are 30.5 and 22.9 °C, respectively. Relative humidity varies from 55 to 65% during the day and falls to about 40% during the major dry season (Obuobie and Barry 2010). In terms of averages, the annual aridity index averages about 0.54, whereas the average wind speed is 251 km day. The average sunshine hours and solar radiation are 6.5 h and 18.6 $MJ\,m^{-2}\,day^{-1}$, respectively. Annual potential evaporation is about 1504 mm (Gordon et al. 2003).

The vegetation consists mainly of grassland interspersed with dense short thickets often less than 5 m high with a few trees such as *Antiaris africana*, *Ceiba pentandra*, *Milicia excelsa*, *Albizia zygi*, and *Azadirachta indica*. Short and medium grasses are the dominant plant species, notable among which are *Andropogon gayanus* and *Hyparrhenia dissolute* in upland areas and *Vetiveria fulbibarbis*, *Brachiaria falcifera*, and *Bothriochloa bladhii* in low-lying areas.

The dominant soils of the zone include Acrisols, Cambisols, Gleysols, Luvisols, Solonetz, Vertisols, and intergrades (Obuobie and Barry 2010).

Within the Volta Basin, the coastal zone extends about 2 km off the estuary to about 80 km upstream, forming the area referred to as the Lower Volta Basin. Important towns within the zone include Akuse, Aveyime, Bator, Mepe, Adidome, Sogakope, Big Ada, and Dabala (EPA 2002).

5.19.5.2 Mangrove Ecosystem

Mangrove ecosystems are limited to a very narrow, noncontinuous coastal area around lagoons and on the fringes of the Volta River estuary. The ecosystem consists of water, muddy soil, trees, shrubs, and their associated flora, fauna, and microbes. Together with the associated wetlands, they provide habitat for high concentrations of birds, mammals, reptiles, amphibians, fish, and invertebrate species. In Ghana, the mangrove forest covers a total area of about 100 km^2, but it is much more limited in the Volta Basin where activities of local people continue to degrade the ecosystem (Finlayson et al. 1998). This area serves as a nursery site for commercial marine fishes and shrimps and is known globally as a significant habitat for migrating birds. As a result of the ecological wealth of this zone, the Keta and the Songhor Lagoons, which form integral parts of the zone, have been designated as Ramsar sites (Rubin et al. 1998).

The most common mangrove species found in Ghana are *Rhizophora racemosa*, *Avicennia nitida*, and *Drepanocarpus lunatus* (a climber). The combined effects of human activities and cessation of annual flooding within the lower reaches of the Volta has resulted in an increase in the abundance of weeds, particularly the bulrush *Typha domingensis* (*T. australis*), the fern *Acrostichum aureum*, rhizomatous grass *Paspalum vaginatum*, club rush *Cyperus articulatus*, and two spreading, succulent herbs, *Sesuvium portulacastrum* and *Philoxerus vermicularis* (Boko et al. 2007).

Mangroves have the potential to curtail the adverse effects of flooding associated with sea level rise especially in the event of climatic change. As Boko et al. (2007) state, the projection of sea level rise could, among other things, increase flooding and increase the high socioeconomic and physical vulnerability of coastal cities. Mangrove ecosystems conservation should therefore be a collective responsibility, with a high degree of local involvement.

5.19.5.3 The Semideciduous Forest

The SDF zone in Ghana is located above the high forest zone and has an aerial extent of about 66 300 km^2. It covers a very extensive area, constituting about 90% of the total forest zone. The zone is characterized by a bimodal rainfall distribution pattern, with mean annual totals ranging from 1400 to 1750 mm. Temperatures are generally high throughout the year. The mean annual temperature is about 27 °C, with an annual mean variation of 31 and 20.6 °C in the hottest and coolest months, respectively. The relative humidity could be as high as 90% in the mornings and during the wet seasons but falls below 80% during the dry seasons. The potential evapotranspiration is about 1350 mm year^{-1} (Obuobie and Barry 2010).

The associated trees in the SDF include *Afzelia africana*, *Albizia adianthifolia*, *C. pentandra*, *Cola caricifolia*, *Cola gigantea*, *Diospyros mespiliformis*, *Elaeis guineensis*, *Malacantha alnifolia*, *Sterculia tragacantha*, *Anchomanes* sp., *A. africana* and *Chlorophora excelsa*. A major characteristic feature of the SDF is that the trees shed their leaves during the dry season (Obuobie and Barry 2010).

The zone supports most of Ghana's food crops, such as maize, cassava, and plantain, as well as major commercial crops, namely, cocoa and oil palm. In addition, most of the timber for both local consumption and export comes from the zone. Soils present in this zone are Acrisols, Nitrisols, and Gleysols (Obuobie and Barry 2010).

The SDF zone is not very extensive, as the Volta, within this zone, flows between two mountain ranges before crossing the gorge where the Akosombo dam was created, thus making the basin very narrow. In addition, the SDF zone by itself is very extensive in the western part of the country but narrows up toward the east where the basin is to be found. The zone covers parts of the Eastern, Ashanti, Brong Ahafo, and Volta Regions. Crop cultivation is not widespread within the gorge area, as farming is prohibited here for strategic reasons. Elsewhere major crops including all the aforementioned are extensively cultivated.

5.19.5.4 The Forest–Savanna Transitional Zone (Derived Savanna)

The forest–savanna transition zone covers about 8300 km^2. It is located above the SDF zone and extends across the entire middle belt zone of the country. The zone is also characterized by two rainfall maxima regimes, with mean annual totals ranging from 1200 to 1400 mm. Temperatures are on average high with an annual mean of about 26.5 °C. Morning and midday relative humidity values range between 85 and 88% and 70 and 74%, respectively. Potential evapotranspiration in this zone is about 1350 mm year^{-1} (Obuobie and Barry 2010).

The zone contains a mix of both savanna and forest tree species, with most of them shedding their leaves during the dry season. Species such as *Daniella oliveri*, *Borassus aethiopum*, and *Terminalia macroptera* also occur. These trees occur in association with tall to medium grass such as andropogon and *Pennisetum* spp. The soil types here are Lixisols, Nitrisols, Plinthosols, and Cambisols (Obuobie and Barry 2010).

This zone is the second largest agroecological zone within the basin after the guinea savanna zone. It covers the Afram Plains portion of the eastern and Ashanti Regions, the mid and northern portions of the Volta Region, and parts of the Brong Ahafo Region. Major crops cultivated in this zone include maize, yam, cassava, groundnuts, and cowpeas. The area is also extensively grazed by cattle (Gyasi 1997; Nsia-Gyabaah et al. 1994).

5.19.5.5 Guinea Savanna Zone

The guinea savanna zone has an aerial extent of about 147 900 km^2 and is by far the largest agroecological zone in the country. This zone is characterized by a single maxima rainfall regime, which begins from April and ends in October. The mean annual rainfall varies between 1000 and 1200 mm. The dry season is experienced within the months of November to March when the desiccating effect of the harmattan that blows across the Sahara Desert is strongly felt. The mean annual temperature ranges between 27.8 and 28.5 °C. Compared to the forest zone, the guinea savanna has a wide range of temperatures, with the highest annual mean ranging between 33 and 35 °C and the lowest annual mean of about 22 °C. The relative humidity of the zone is about 40% in the dry season but may reach 84% in August, the peak of the rainy season. Potential evapotranspiration is very high and varies between 2000 and 2300 mm year^{-1} (Obuobie and Barry 2010).

The associated vegetation consists typically of grasses of varying heights interspersed with fire resistant, deciduous, broad-leaved, and gnarled trees at the forest margins in the south. Toward the north, the vegetation grades into a more open grassland with widely spaced shorter trees. The grasses dry up during the dry season and are usually burnt by illegal herders and hunters. The most common grass species include *A. gayanus*, *Heteropogon* spp. and *Cymbopogo gigantus*. *Vetiveria nigritana*, *Seteria anceps*, and sedges also occur in alluvial sites. The common tree species include *Lophira lanceolata*, *Anogeissus* spp., *A. africana*, *Prosopis africana*, *Pterocarpus erinaceus*, *Parkia clappertoniana*, *Butyrospermum parkii*, and *A. africana*. Fringe forests and woodlands may be found along the watercourses. Soils present in this zone are Lixisols, Acrisols, Luvisols, and Gleysols (Obuobie and Barry 2010).

The guinea savanna agroecological zone spans about two-thirds of the Volta Basin, covering northern parts of the Brong Ahafo and the Northern and Upper West Regions. The zone also covers the greater part of the Upper East Region save for the northeastern corner where the Sudan Savanna is found. Intense human activities including farming, logging, fuel wood extraction, and bush burning within this zone make it very vulnerable and susceptible to flooding and other extreme events (Biney 1990). Crops cultivated here include maize, sorghum, yam, groundnuts, millet, beans, and cowpeas.

5.19.5.6 Sudan Savanna Zone

The last agroecological zone of the Volta Basin within Ghana is the Sudan savanna zone. It extends into Ivory Coast and Burkina Faso to the west and north, respectively, and covers an estimated area of 1900 km^2. It is also characterized by a single rainfall maxima regime and experiences annual average rainfall varying between 900 and 1000 mm. Mean annual maximum temperature ranges from 27.8 to 28.5 °C. Relative humidity is about 40% in the dry season but may reach 84% in August, just as the in the guinea savanna zone. Potential evapotranspiration is also similar to that of the guinea savanna zone (Obuobie and Barry 2010).

The vegetation type is open grass with scattered short drought- and fire-resistant deciduous trees. Grass cover is very sparse, and in most areas, the land is bare and severely eroded. The dominant trees in the zone include *Adansonia digitata*, *C. pentandra*, *B. parkii*, *P. clappertoniana*, *Tamarindus indica*, and *Acacia albida*. The soil types here are Lixisols, Acrisols, Luvisols, and Lithosols (Obuobie and Barry 2010).

The Sudan savanna zone within the Volta Basin is limited to a very narrow strip in the northeastern borders of Ghana with Burkina Faso. The zone is susceptible to desertification, and there is the fear that increased human activities could bring this about sooner than later (Biney 1990). The most common crops cultivated include sorghum, millet, maize, groundnuts, and cowpeas (Figure 7).

5.19.6 The History of Development of the Volta Basin

5.19.6.1 Changes in Water Supply and Use

Changes in water supply and use within the Volta Basin reflect changes due to increase in population pressure and use of water for agricultural, industrial, and electricity generating purposes. There has been an increase in the number of large and small dams also as a consequence of increased population pressure.

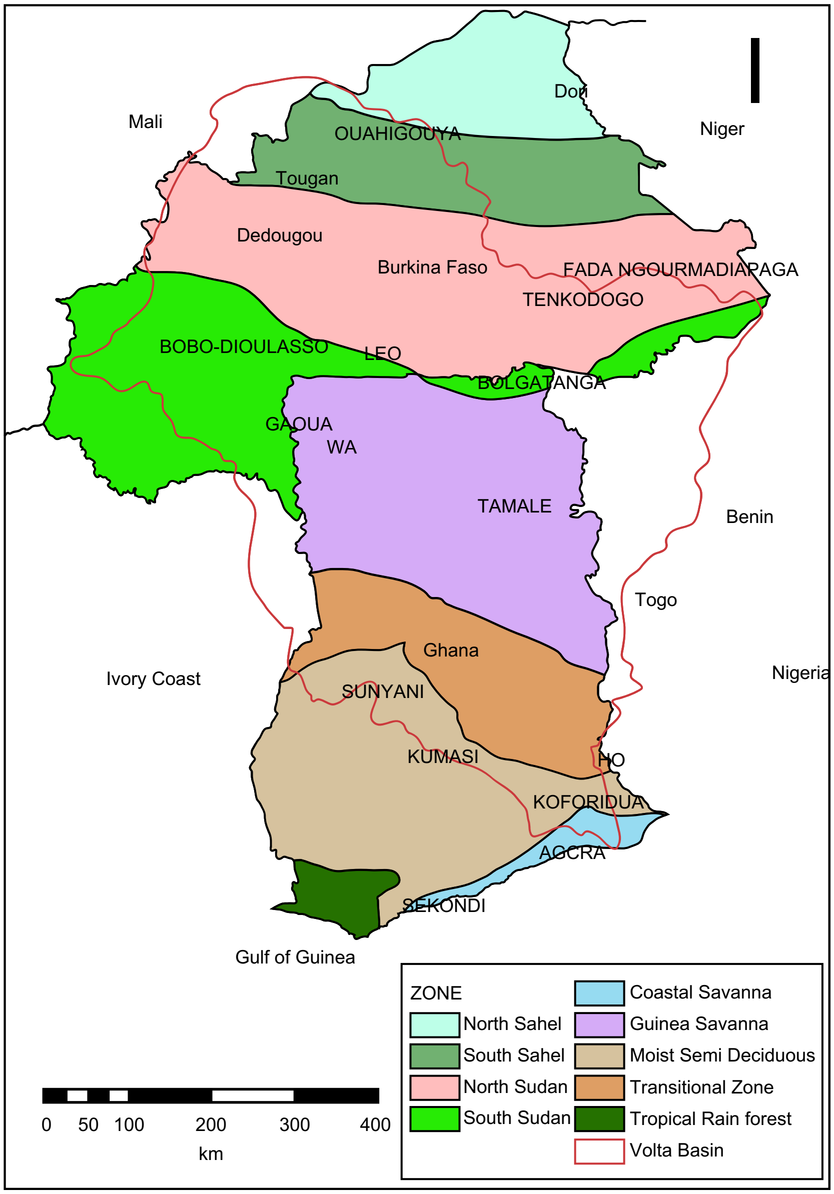
As a result of the damming of the Volta River at Akosombo, one of the largest manmade lakes in the world has been created, covering an area of approximately 8500 km^2. A smaller and shallower impoundment, the Kpong Headpond, which covers an area of roughly 38 km^2 with a storage capacity of 2000×10^6 m^3, was completed in 1981 when another hydroelectric dam was constructed at Kpong, 20 km downstream of Akosombo (Obuobie and Barry 2010). The construction of the Kpong dam has resulted in near pollution-free water emanating downstream of Akosombo and hence improving the water quality (Ansa-Asare and Asante 1998). Within the West African region, Benin has a hydroelectric power station on the Oti River, with a storage capacity of 350 million m^3 and the capacity to produce 15 MW. In addition, a hydroelectric power station has been planned at Pouya (Natitingou) on the Yeripae.

In Burkina Faso, in recent decades, there has been a push to increase the number of dams in the Volta Basin to meet the country's need and demand for fresh water. As a result, there are now estimates of between 600 and 1400 dams and lakes with a total storage capacity of 4.7 billion m^3 and about 10 484 wells of which 8020 are in good condition (Obuobie and Barry 2010). The volume stored annually in these reservoirs is about 2490 billion m^3. On hydropower, 13 locations have been identified in the country and 10 are located within the Volta Basin. Several planned irrigation projects covering a total area of 1045 ha will require about 65.3 million m^3 according to an estimate (Obuobie and Barry 2010).

5.19.6.2 Hydro-Development

The Akosombo dam in Ghana is the most significant structure built in the Volta Basin, resulting in the formation of the Volta Lake. The seasonal rise and fall is about 2.0–6.0 m, and the areas covered by seasonal fluctuations are about 100 000 ha (Obuobie and Barry 2010). Water available from the Volta Lake reservoir is used primarily for hydro energy production, transportation, fishery, tourism, and irrigation. The Akosombo dam generates 80% of the power produced in Ghana and is of strategic importance to the economy of the country. The primary purpose of the project was to supply cheap electricity to smelt aluminum, and the secondary one is the development of the country.

When the lake was constructed, it led to the resettlement of about 80 000 people from several hundred villages to 50 newly built townships (more than 1% of Ghana's population at that time). In addition to the resettlement of the river communities, damming affected local health, agriculture, fishing, and navigation (Obuobie and Barry 2010).


Mali
Niger
Dori
OUAHIGOUYA
Tougan
Dedougou
Burkina Faso
FADA NGOURMADIAPAGA
TENKODOGO
BOBO-DIOULASSO
LEO
BOLGATANGA
GAOUA
WA
TAMALE
Benin
Togo
Ghana
Nigeria
Ivory Coast
SUNYANI
KUMASI
HO
KOFORIDUA
ACCRA
SEKONDI
Gulf of Guinea
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km
ZONE
North Sahel
South Sahel
North Sudan
South Sudan
Coastal Savanna
Guinea Savanna
Moist Semi Deciduous
Transitional Zone
Tropical Rain forest
Volta Basin

Figure 7 Agroecological zones of the Volta Basin.

Several years after the Akosombo dam was built, the Kpong headpond (reservoir) was built in 1981, which created the potential for two industries, agriculture by irrigation and fishing (Vanderpuye 1982). In 1982, for example, the reservoir produced about 463–618 metric tons of fish (GEF-UNEP 2002) and serves as the main source of water supply to the Accra-Tema metropolitan areas of Ghana.

5.19.6.3 Water Institutions and Legislation

Institutions related to water resources management and legislations have evolved to manage the water resources of the Volta, both in relation to its hydroelectric usage and its use for domestic and commercial purposes. Some of the relevant acts for establishing new institutions and strengthening existing ones when it comes to managing water resources in Ghana, and in particular the Volta Basin are as follows:

- Act 46 of 1961 (Volta River Development Act) sets up the Volta River Authority (VRA) with mandate to plan, execute, and manage the development of the Volta River. Subsequent Acts such as Act 490 of 1994 establishes the Environmental Protection Agency (EPA) of Ghana.
- Act 522 of 1996 establishes the Water Resources Commission.

Also, there are institutional structures and legal frameworks established in the riparian countries of the Volta Basin for environmental management and documented by various country reports as summarized in Table 5.

Table 5 Some ministries and departments for managing water and land resources in the Volta Basin

Country	*Ministry*	*Department/Institute*	*Responsibilities*
Benin	Agriculture, livestock, and fishing	Rural development, forest and natural resources, agriculture, fishing, and livestock	Management of natural resources, water, and soil
Benin	Mines, energy, and hydraulics	Mining, Beninois Society of Electricity and Water, and hydraulics	Management of mineral resources, management and distribution of water resources at the national level
Burkina Faso	–	Foreign affairs	Implementation of framework of agreements of international cooperation
Cote d'Ivoire	Mines and energy	–	Generation of hydroelectricity
Cote d'Ivoire	Environment and life	–	Protection of water
Ghana	Works and housing	Water Resources Commission	Planning and regulation of the development and use of freshwater resources in Ghana
Ghana	Environment, science, and technology	Environmental Protection Agency (EPA)	Management of country's environment, collaborating with relevant state institutions and international bodies in ensuring sustainable development of the country's natural resources
Ghana	Energy	Volta River Authority (VRA)	Plan, execute, and manage the development if the Volta River for hydropower generation

Culled from Barry, B., E. Oboubie, M. Andreini, W. Andah, M. Pluquet, 2005: Comprehensive assessment of water management in agriculture. Comparative study of river basin development and management. Draft report to International Water Management Institute and Comprehensive Assessment of Water Management in Agriculture.

5.19.6.4 Policy Frameworks and Water Visions

The water policy of Ghana aims at achieving an efficient and effective management system for the sustainable development of water resources in Ghana to assume full socioeconomic benefits for present and future generations (Obuobie and Barry 2010). This is against the backdrop that water is essential to man and all living things and that health, nutrition, and food production, for example, depend on its availability in adequate quantities and good quality.

Among others, Ghana's water policy is guided by the following:

- The principle of fundamental right of all people to safe and adequate water to meet basic human needs.
- The principle of recognizing water as a finite and vulnerable resource, given its multiple uses and the principle of polluter pays, to serve as a disincentive to uncontrolled discharge of pollutants into the environment.

In line with these principles, steps have been taken in the basin to create a policy environment that promotes sustainable water resource management. The preamble to the water vision recognizes that population increase, rapid urbanization, and industrialization have made water increasingly scarce and often of low or reduced quality (Obuobie and Barry 2010). If regional climate statsitics change so as to increase both the spatial and temporal unpredictability of water availability, to reduce the risk to such a change, the Ghana water vision for 2025 has the main objective to "promote an efficient and effective management system and environmentally sound development of all water resources in Ghana" (Obuobie and Barry 2010).

In line with the water vision, there has been a strategic action plan for the Volta (Andah and Gichuki 2005), with priority areas focusing on the following:

- Policy actions
- Legislative/regulatory reform
- Institutional strengthening
- Capacity building
- Investment
- Scientific investigation
- Data management

An overview of aspects of legal and regulatory interventions needed to achieve environmental quality objective such as a balanced aquatic ecosystem is provided in Table 6.

5.19.6.5 Overview of National, Institutional, and Legal Framework for Integrated Management

In the countries of the Volta Basin, there are many if not too many institutions in charge of managing water resources. This has sometimes resulted in the overlapping of responsibilities and difficulties in coordination. Coordination of activities among the institutions was found to be generally weak (Obuobie and Barry 2010). An integrated approach at the local and national levels with emphasis on intersectoral coordination has been proposed.

The current legal framework in relation to the effectiveness of the laws governing resources appears to be weak and ineffective (Obuobie and Barry 2010). In many cases, laws are adequate but are not adhered to or enforced. This has mostly been due to lack of institutional capacity or political commitment.

Table 6 Aspects of proposed legislative and regulatory interventions to achieve environmental quality objectives in the Volta Basin

Environmental quality objective	*Targets*	*Activities*	*Interventions*	*Type of intervention*	*Root causes*
Balanced aquatic ecosystem	Achieve adequate surface water quality by 2012	Establish common methods for assessing water and sediment quality including bioassays of coastal biota	Develop guidelines for methods of water, sediment, and biota monitoring and assessment (including sampling, analysis, and risk assessment)	Legislative/ regulatory	Insufficient scientific capacity
			Implement a first periodic assessment (3-year interval) of the river quality and trends	Investment	
			Develop and establish national/regional land-based activities data and information management system as a tool for contaminant assessment and management	Data management	
		Fill gaps in knowledge of priority pollutants (contaminant levels) and major sources of pollutants (contaminant inputs)	Conduct regional assessment of priority land-based activities, sources of contaminants, and pollutant levels in water and sediments	Scientific investigation	Insufficient scientific capacity
			Conduct routine targeted monitoring of riverine sediments and biota for purposes of identifying major hot spots of pollution and land-based activities	Investment	
		Exchange environmental data and information	Develop agreements and technology basis for the free and regular exchange of environmental data and information within the region	Data management	Insufficient scientific capacity; inadequate technical infrastructure
		Reduce impacts of urban areas on water quality	Construct or extend sewage collection systems in all major cities in the basin and route discharges to treatment plant	Investment	
			Upgrade/renovate existing treatment plants for mechanical and biological treatment	Investment	
			Expand solid waste collection in all major cities and improve disposal methods so waste does not runoff or leach into waterways	Investment	

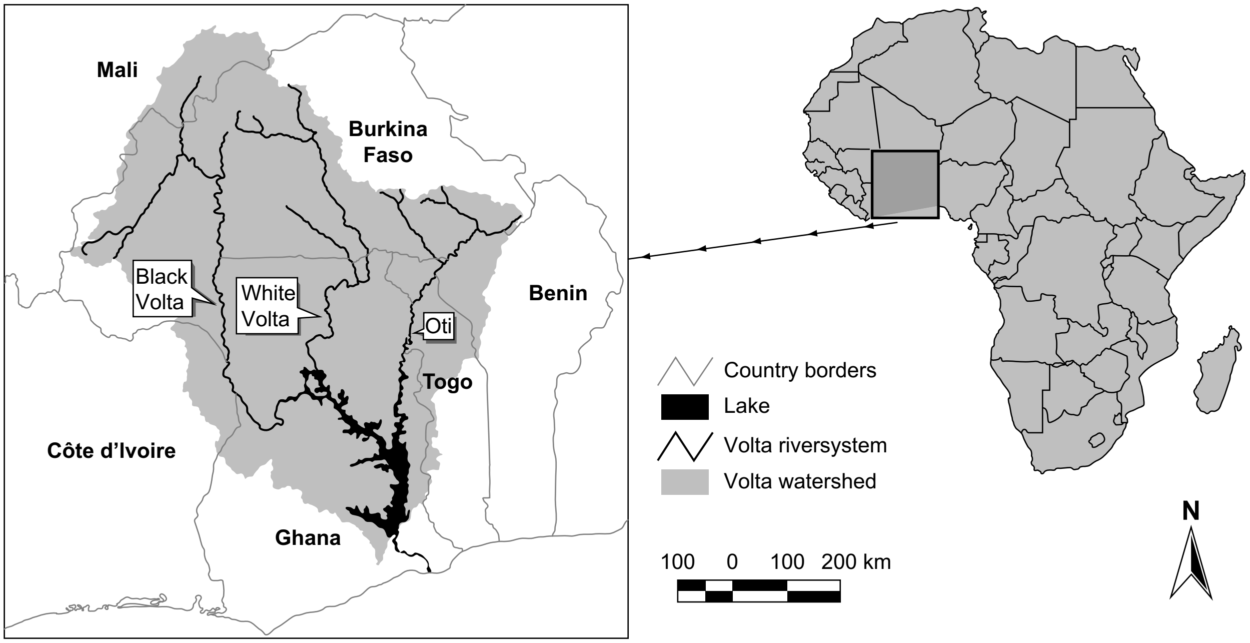

Figure 8 The Volta Basin.

5.19.6.5.1 Regional Coordination

There have been several initiatives at the regional level to manage water resources. For example, the West African Regional Action Plan for Integrated Water Resources Management (WARAP-IWRM) was initiated by the Government of Burkina Faso with the support of Danish International Development Agency (DANIDA). This regional cooperation arrangement that started in 1997 within the Economic Community of West African States (ECOWAS) has proposed the establishment of a regional structure for coordinating and monitoring the West African Regional Initiatives for Integrated Water Resources Management.

Another regional cooperation effort for the integrated management of water resources is being developed by the Global Water Partnership (GWP) and its technical group, the West African Technical Advisory Committee (WATAC), with the aim of preparing regional programs of action to implement the West African water vision for the twenty-first century.

Other initiatives in the region include the GLOWA Volta Project on integrated assessment of feedback mechanism between climate, land use, and hydrology.

In addition to multilateral cooperation, bilateral cooperation also exists among the riparian countries of the Volta for mitigating environmental issues and problems. Such cooperation efforts include the Burkina Faso–Ghana Joint Committee for managing the water resources of the Volta Basin as well as Burkina Faso–Cote d'Ivoire committee for the development of programs for integrated management of water and cooperation in matters of environment and forest, for example.

5.19.7 Social Issues in the Volta Basin

5.19.7.1 Population

The countries of the Volta Basin are among the fastest growing populations in the world. Burkina Faso represents 43% of the total area of the basin, and about 78% of the total population lives in the Volta Basin. In Togo, the Volta Basin covers 48% of the country's land and was home to 35% of the total population in 2000 (Obuobie and Barry 2010). The Volta Basin has an estimated population of approximately 25 million people, growing at a rate of 2.5% year^{-1}. The population of the Volta Basin is estimated to increase by as much as 80% over the next 25 years (Andah 2005) (Figure 8, Table 7).

5.19.7.1.1 Population Distribution

Population density within the countries that make up the Volta Basin vary, with the highest found in Togo (118 km^{-2}), followed by Ghana (86 km^{-2}), and the lowest in Mali (9 km^{-2}) (Table 8). However, there are also intracountry variations in the geographic distribution of population. For example, the population density of Ghana's Upper East Regions is 104 persons per km^2, while that of the Northern Region is only 26 persons per km^2. In Côte d'Ivoire, the population density varies from 8 persons per km^2 in the north to 22 persons per km^2 in the south (Gordon and Amatekpor 1999). The average population density in the Volta Basin of Burkina Faso is

Table 7 Population of Volta Basin

Country	*Basin area (%)*	*Population (%)*
Benin	3.41	2.56
Burkina Faso	42.9	47.6
Cote d'Ivoire	2.48	2.13
Ghana	41.6	35.8
Mali	3.12	3.35
Togo	6.41	8.55

Source: Biney, C., 2010: Transboundary water resources management in the Volta Basin. Paper presented at the 8th World General Assembly, Inbo, Dakar (Senegal), 20–23 January 2010.

Table 8 Population dynamics in the Volta Basin

Country	Total population (millions 2008)	Population density (people per km, 2008)	Population growth rate (annual %)	Population ages 0–14 (% of total)	Population ages 15–64 (% of total)	Population ages 65 and above (%)	Gross domestic product	
							Growth (%)	Per capita growth (%)
Benin	8.7	78	2.56	45.8	51.4	2.7	5.1	1.8
Burkina Faso	15.2	56	2.38	47.1	50.1	2.7	4.5	1.0
Côte d'Ivoire	20.6	65	2.20	41.9	55.1	2.5	2.2	−0.1
Ghana	23.4	103	1.83	43.1	51.9	4.5	7.3	5.1
Mali	12.7	10	2.25	46.9	49.8	3.0	5.0	2.5
Togo	6.5	119	2.40	43.6	52.6	3.2	1.1	–1.4

Source: World Bank, 2003: World Development Indicators, World Bank, Washington, DC; World Bank, 2010: *World Development Indicators*, World Bank, Washington, DC.

29 inhabitants per km^2, with a high population density (79 inhabitants per km^2) on the Central Plateau and sparsely populated eastern and western regions (10 inhabitants per km^2) (Obuobie and Barry 2010).

5.19.7.1.2 Population Structure

The population of the basin is young. The major portion of the basin population falls into the working age group of 15–64 years. The basin's population is also largely rural (between 56% and 83%). The countries with the lowest percentage of rural population, Côte d'Ivoire and Benin, have over 50% of their people living in the rural areas, whereas Ghana, Mali, and Togo have close to 66% of their people living in rural areas (Obuobie and Barry 2010).

5.19.7.1.3 Migration

Migration in the Volta Basin is influenced by a number of factors such as poverty, increasing population pressure, and environmental degradation. The easy movement of people across national boundaries in the subregion under the ECOWAS protocol makes population pressure a transboundary cause of many of the environmental problems in the basin. For example, the establishment of the Volta Lake upstream in Ghana resulted in a decline in the fishing industry in the Lower Volta, causing people to move upstream to live near the lake for their livelihood. In Togo, some people in the basin (Savannas and Kara regions) who migrated to the southern regions of the country before 1990 are now returning because of sociopolitical unrest (Obuobie and Barry 2010; World Bank 2010). The population of Burkina Faso experiences an important migration at both internal and external levels. It is estimated that of 100 migrants, 71.2% migrate inside the country and 28.8% abroad (Obuobie and Barry 2010).

5.19.7.2 Human Resources

The young-age structure of the Volta Basin presents opportunity in terms of human resources. However, low educational levels as well as poor access to health facilities in many parts of the Volta Basin have affected the quality of human resources available. Hence, social development in the basin's countries remains problematic.

5.19.7.2.1 Education and Literacy

Although many of the basin countries such as Ghana have made important strides toward reaching the Millennium Development Goal of achieving universal primary education, there are still significant disparities in the schooling and literacy rates for males and females within the countries in the basin. For example, primary completion rates are still lower for females (Table 9). Female intake rates are generally lower than male for all countries, except Ghana. Adult literacy rates for males and females are worst for Burkina Faso and Mali, with Benin and Côte d'Ivoire in the middle. Female illiteracy rates are higher than male illiteracy rates

Table 9 Education and literacy levels in the Volta River Basin countries

Country	Gross primary enrollment ratio	Net primary enrollment ratio	Adjusted net enrollment ratio, primary		Primary completion rate	Adult literacy	
			Male 2008	Female		Male	Female
Benin	117	93	99	86	65	54	28
Burkina	79b	63b	68b	60b	38	37	22
	74	–	–	–	48	64	44
Ghana	102	74	74	75	79	72	59
Mali	91	72	81	68	57	35	18
Togo	105	83	91	80	61	77	54

Source: World Bank, 2010: *World Development Indicators*, World Bank, Washington, DC.

for all countries in the Volta Basin (Asante 2006). These disparities are the bases of existing gender issues related to differential access to resources, distribution, and processing, where women currently play a significant role, yet are often marginalized.

5.19.7.2.2 Health

In Ghana there have been serious health issues associated with the Volta Lake, in particular the two major diseases schistomiasis (or bilharziasis) and onchocerciasis (or river blindness). The dam virtually halted the rate of flow in the Volta River, increasing stagnant water conditions and, consequently, creating ideal breeding grounds for carriers of waterborne diseases. Before the construction of the Akosombo and Kpong dams, malaria (from mosquitoes) was not much of a problem along the swift-flowing Volta River, but after it became a stagnant lake, malaria became a greater public health concern in lakeside villages. Likewise, only 1–5% of the population suffered from schistosomiasis (a disease transmitted by snails) before the dam was constructed (Obuobie and Barry 2010). Before the creation of the Volta Lake, infection rates of schistosomiasis in the area had been 1–5%. The problem of Bilharzia in the lake basin must be seen as a disease, which embraces both the lake and the Volta Delta. The migratory habits of the fishermen ensure the spread of the disease from endemic to other areas. The construction of the second dam at Kpong also eliminated the breeding sites downstream of Akosombo and therefore stopped the transmission of the disease in the vicinity. Despite the increases in health facilities across the countries, infectious diseases are still the main cause of death among poor people.

5.19.7.3 Living Standards

The gross domestic product (GDP) is the sum of value added by all resident producers plus any product taxes (less subsidies) not included in the valuation of output. Growth is calculated from constant price GDP data in local currency (Asante 2006). The Volta River Basin countries, except Ghana and Togo, are considered to have low human development and possess underdeveloped economies (Table 10). They are described as being among the poorest nations in the world, with an average per capita GDP of about US\$ 1500 year^{-1}. Mali, Burkina Faso, Benin, and Ghana have more than 70% of their population living below the US\$2 a day poverty line. Four main causes of poverty have been identified in the Ghana part of the Volta Basin (Asante 2007; Nick Van De Giesen et al. 2001):

- Type of available economic activities (fishing, agriculture)
- Degree of water insecurity (poor access, health impacts, loss of labor)
- Environmental impact of upstream catchment activities (dams, farming practices)
- Water-related diseases (malaria, guinea worm, etc.)

Table 10 Macroeconomic indicators in the Volta River Basin countries

Country	GDP per capita 2006 (US$)	2007/2008 human development index	Population living below US\$1 day^{-1} (%)
Benin	536	163	31
Burkina Faso	416	176	27
Côte d'Ivoire	952	166	15
Ghana	532	135	45
Mali	498	173	36
Togo	356	152	Not available
Average	550	–	31

GDP, gross domestic product.
Source: Gao, Y., and A. Margolies, 2009: Transboundary water governance in the Volta River Basin.

5.19.7.3.1 Access to Potable Water

Access to safe drinking water varies from 50 to 84%. In general, access to safe drinking water is lower in rural areas than in urban areas. The majority of the population lives in rural areas, with agriculture being the most important occupation. The number of rural households having access to safe water from boreholes, pumps, or piped water taps is only 53%, compared to 83.3% in the urban area. Among the most extreme rural poor only 51% have access to safe water, while among the least poor, 73% have safe water.

5.19.7.4 Income and Employment

About half the population in each of the riparian countries is in the age group of 15–64 years, which forms the majority of the labor force. This age pattern theoretically means that the basin is significantly rich in human resources. Among the six basin countries, Ghana has the largest labor force (9.5 million), followed by Côte d'Ivoire (6.6 million), Burkina Faso (5.7 million), Mali (5.4 million), Benin (2.9 million), and Togo (1.9 million). In the Ghanaian part of the Volta Basin, 80% of the population is rural and 20% urban.

The basin countries are largely rural (64–88 %), and the people depend, to a large extent, on the exploitation of natural resources for their livelihood. The agriculture sector employs the largest share of the labor force (60–92%) (Obuobie and Barry 2010). Economic development depends on agriculture because no alternatives exist in other sectors. Staple crops are sorghum, millet, and corn grown under rain-fed conditions. Average yield lies between 800 and 1000 kg of grain per hectare. Irrigation is generally seen as necessary to control the risks in order to achieve sustained higher levels of production (Benneh 1973). The high population density on the central plateau, which lies entirely within the Volta Basin, and the high levels of intensive farming (between 50 and 70%) mean that the agrodemographic threshold has been reached, if not exceeded, and has led to a process of land degradation. Agriculture generally employs more women than men. For example, in Côte d'Ivoire, agriculture accounts for 54% of male employment but 72% of female employment (Obuobie and Barry 2010).

The services sector is next to agriculture (6–30%), with industry ranking third (2–16%). The services sector is dominant in the urban areas, whereas agriculture dominates in the rural areas. Burkina Faso has only minor mining and industrial sectors.

5.19.8 Major Farming Systems and Land Tenure in the Volta Basin

5.19.8.1 Bush Fallow

The bush fallow system of farming is widely practised in all the agroecological zones of the Volta Basin. Under this farming system, the family or household is the unit of decision making and production, and there is heavy reliance on personal and family labor for farming activities. The farming system is characterized by the use of simple tools and fire for clearing vegetation, and there is heavy dependence on the inherent fertility of the soil (Hunter 1969). The use of fire is a means of conserving energy, and the ash from burning makes some minerals (phosphates and potash) readily available for use by plants. Crops grown are basic food staples including cassava, yam, cocoyam, plantain, maize, and vegetables. Farm sizes are usually small, and the cropping system adopted is mixed, which help provide the subsistence needs of the family. Land ownership is communal, and the right to cultivate a piece of land is a birthright and/or with the consent of the land-owning group (Hunter 1969).

The bush fallowing practice involves cultivation of parcels of land on a rotational basis, because a piece of land gets exhausted after two or three successive periods of cultivation. In the forest agroecological zone in particular, there is close relationship between the soil and vegetation in terms of nutrient exchange. Clearing of the vegetation breaks this normal cycle, and the soil loses its nutrients through leaching. The farmer is therefore compelled to abandon the deficient land for it to restore its fertility through the natural nutrient exchange cycle. Thus, there is rotation of fields instead of crops (Hunter 1969). The length of the fallow period varies from place to place depending on prevailing local ecological and sociocultural factors. Essentially, there should be plenty of cultivable land in relation to the population of the land-owning group so that pieces of land could be allowed sufficient time to regain their fertility through the natural system. However, increasing pressure on land in most districts has led to shortening of fallow periods from between 6 and 10 years to between 2 and 3 years (Hunter 1969). Consequently, most lands are not able to regain their fertility, leading to poor crop yields.

Benneh (1973) identified two types of bush fallow systems, the mosaic pattern of land use and the strip pattern of land ownership. The latter is associated with the huza system of the Krobos. It originated when groups of people organized themselves to purchase lands, which were distributed on the basis of individuals' capital contribution. The distribution was done from a common baseline, giving rise to the strip pattern. The group, however, became a coherent social unit with a leader and team of elders responsible for ensuring peace among members and settling potential boundary disputes.

The bush fallow system remains the dominant mode of producing major food crops in the country, for which the forest–savannah transitional zone is noted. Increase in land area under cultivation constitutes the dominant mode of increasing agricultural production. This trend has left a legacy of widespread devegetation/deforestation, which threatens the very basis of this farming system. Also, as the number of members of the land-owning group increases, the land becomes progressively fragmented, farm sizes are drastically reduced, and fallow periods are shortened. Indeed, trends in population growth, increasing demands on the agricultural industry, increased recognition of the value of land, and changes in societal organization as a whole are gradually transforming the bush fallowing system of farming. The fundamental challenge is how to utilize lands effectively to achieve the desired levels of food production to feed the increasing population against the backdrop of land cover transformation and climatic change. Not surprisingly therefore, farmers are increasingly adopting the use of agrochemicals (fertilizers and pesticides), tractors, and other farming techniques to achieve higher crop yield.

5.19.8.2 Permanent Systems

Permanent field cultivation has been associated with traditional cash crop production in the forest region. The crops involved are cocoa, oil palm, rubber, and kola for the market (Hunter 1969). In recent times, however, and particularly in the forest–savannah transitional zone, cashew and mango have become very important tree crops. The nutrient status of the soil under this farming system is largely assured through decomposition of dead vegetation from the crops on the land. The produce is sold for cash. Tree crops may be interplanted with food crops in the initial stages of the farm when the tree canopies are not well formed. Cocoa trees are necessarily interplanted with food crops such as plantain and bananas.

Farm sizes are relatively bigger, and there is the use of hired labor. The right of use of land for cash crop farming is usually guaranteed for fairly longer periods through outright purchase or long leasehold. Share-cropping arrangements also exist between land owners and tenants. Individuals belonging to land-owning groups negotiate with members of their respective groups for putting lands under permanent field cultivation. Benneh (1973) has indicated that a member of the land-holding group who grows cash tree crops has greater control over his piece of land, which strengthens the individual's interests in the land. This could be understood as one of the ways in which the traditional land tenure system is being transformed.

5.19.8.3 Compound Farming

Compound farming is undertaken in the savannah agroecological zone of northern Ghana. It involves permanent utilization of land immediately surrounding a homestead for crop cultivation, hence the name compound farming. Household refuse and animal droppings are used to improve the fertility of the soil, ensuring sustainable crop cultivation. However, the intensity of use of manure diminishes radially outward from the housing structures (Tonah 2001). Crops grown are also varied and include leguminous leafy vegetables, groundnuts, and beans, as well as early maturing varieties of guinea corn and maize, which the household depends on while working on distant farms under the bush fallow system. The stalks of harvested guinea corn and maize may be used as fuel. Members of the compound unit consisting of the man, his wives, children, and unmarried brothers and sisters constitute the production and consumption unit. Simple tools including the hoe and the dibble stick are employed for sowing and managing crops on the land.

The layout and pattern of land holdings reflect family structure and stages in community evolution (Tonah 2001). Traditionally, the compound may have several dwellings for members of the whole unit, a granary and a cattle yard. The settlement pattern is dispersed, with each compound having its home farmland. The settlement pattern and agricultural practice are therefore closely interrelated (Tonah 2001). Therefore, the shift from dispersed settlements toward nucleated settlement pattern or concentration of compounds will radically transform the compound farming system. Nucleated settlements have the advantage of planning for the provision of social amenities such as schools, potable water, and clinics.

5.19.8.4 Mixed Farming

Mixed farming is an agronomic practice that integrates elements of both livestock keeping and crop cultivation. The practice is systematic, involving controlled grazing and utilization of animal droppings to improve soil fertility for crop production. The animals are confined and/or controlled when the crops are growing. Once the crops are harvested they are allowed to feed on the stubbles of the grains and remains of other crops. In the process, they spread their droppings on the soils, which in turn improves soil fertility.

Mixed farming was introduced to densely populated northeastern Ghana in the 1930s by the colonial government to check soil deterioration and to increase agricultural productivity (Hunter 1969). Apart from the use of compost from cow dung, animal traction and planting on ridges were also introduced. Production of cow dung for compost was intensified and promoted through stall-feeding of work animals (zero grazing). Farmers also use compost of household refuse and kitchen sweepings and the sweepings from sheep and goat pens.

The development of mixed farming is in response to increased population pressure on land and the need to use land more efficiently to obtain the greatest possible returns. It holds tremendous potential for maintaining the integrity of the environment for increased food production.

5.19.8.5 Livestock Production

Much of the Volta Basin lies within the savannah agro-ecological zone, which is noted for livestock production as in other savannah lands in tropical Africa. Cattle are of great commercial significance. Households also raise goats, sheep, pigs, chicken, and guinea fowl, which are sold to support family income. Women own small ruminants and poultry of various kinds, but cattle are largely the preserve of men. The region is the main supplier of livestock to urban centers in the southern part of the country. The animals are usually transported live in trucks.

The principal cattle breed is the West African Shorthorn, which is hardy and well adapted to the environment. The cattle (and small ruminants) are allowed to roam freely in the dry season and feed on the remains of harvested crops but are confined and restricted during the wet season. The zebu herds have been introduced from neighboring countries by the Fulani, who trek to seek pasture and water. In recent decades there has been increasing number of Fulani pastoralists in the Volta Basin, particularly along the shores of the Volta Lake. The migrant Fulani pastoralists are able to establish reciprocal relationships with the local host populations. They usually reside at the outskirts of villages, keeping their own cattle and those of the indigenous population and other migrants, as well as of urban-based cattle owners (Appawu et al. 2006). The activities of the pastoralists have led to many cases of conflict with crop growers and local people.

5.19.8.6 Interface between Land Evaluation and Farming Systems

The broader issues of use of land for other activities, increasing population, environmental change, and economic and socio-cultural dynamics of society have implications for farming systems. Farmers respond to changes in environmental conditions, land-holding arrangements, technological innovations, market forces, and government policies. For example, high population densities in northeastern Ghana led to the introduction of mixed farming during the 1930s (Hunter 1969), which incorporated elements of the traditional compound farming system. In response to land shortage, farmers in these areas migrate to seek new agricultural lands in less populated areas in the forest–savannah transitional zone of the middle belt of the country.

In the country as a whole, there is growing recognition of the value of land as a major source of wealth. As a result, trustees of land and influential community members engage in outright sale of land and thereby deny other family members the right of use of land. There are also cases of litigation over ill-defined land boundaries, which sometimes lead to communal conflict. These developments together with increasing population have led to progressive fragmentation of agricultural lands and reduction in farm sizes and fallow periods. In the periurban areas, agricultural lands are lost to estate development as the incentives for the sale of lands appear more attractive to land owners. However, in view of growing demand for food in the urban centers, open space in urban and peri-urban areas are utilized for intensive cultivation of mainly vegetables. Such initiatives have become part of the urban land-use structure and hold prospects for promoting urban employment and reducing urban poverty.

Increased environmental pressures such as extraction of wood for fuel will continue to transform farming systems. The forest–savannah transitional zone is the major source of charcoal for urban markets in the southern part of the country. Wood fuel is also an important energy source for a majority of households in the Volta Basin. Continuous wood harvesting, land clearing for new farms, and incessant bush fires have led to reduction in tree stock and drastically reduced the vegetation cover in many areas.

Pressure on land and the need to produce cash crops for sale has gradually brought about innovative farming techniques. There is increasing use of agrochemicals among farmers as they strive to increase crop yield against the backdrop modifications in ecosystems, changes in climatic conditions, and transformations in social arrangements. Drawdown farming along the Volta Lake and flood recession farming in the channels of shallow rivers in the dry season are practiced by farmers in the riparian areas. A number of irrigation schemes such as Tono and

Vea have been in operation since the late 1970s, but there are tremendous opportunities to harness more of the larger rivers for irrigation using appropriate water-lifting technologies.

5.19.9 Health and Environmental Changes in the Volta Basin

5.19.9.1 Prevailing Water-Related Diseases: Pre- and Postimpoundment Era

The prevailing water-related diseases in the Volta Basin, pre-impounment of the river at Akosombo, were yellow fever, malaria, trypanosomiasis (African sleeping sickness), urinary schistosomiasis (bilharzia), and onchoceriasis (river blindness) (World Bank 2010). Although malaria and schistosomiasis were prevalent, they were not much of a problem along the swift-flowing Volta River (Obuobie and Barry 2010). Only 1–5% of the population suffered from schistosomiasis (a disease transmitted by fresh water planorbid snails) before the dam was constructed (Obuobie and Barry 2010).

Yellow fever and dengue were the most important arthropod-transmitted viral infections in the early part of the resettlement period in the lake area (World Bank 2010). The mosquitoes that transmit these infections (*Aedes aegypti*) were found to breed mainly in small collections of water in tins, earthen jars, coconut shells, etc. These health problems were, however, given much attention because of their high fatality rate and subsequently controlled. It may be presumed that yellow fever and dengue have reduced public health significance, and, hence, not much has been reported in recent literature on the infection status of these diseases in the Volta Basin post dam era. Nevertheless, Appawu et al. (2006), in their study on entomological assessment of the risk of transmission of hemorrhagic fever in the Northern Region of Ghana, observed that the main contributory factor to the high larval indices of the vectors was the unavailability of pipe-borne water, which invariably leads to storage of water in pots and barrels for long periods, especially during the dry seasons, in households, which allows for the breeding of *Aedes* sp. The possibility of reimmergence of these conditions are worth investigating, as effects of climatic change with its attendant water shortage will result in storage of water in containers for longer periods, which will provide the appropriate breeding sites for these mosquitoes.

Onchocerciasis, the parasitic disease causing river blindness was very prevalent in the preimpoundment era. Although literature on the prevalence of the disease is limited (Obuobie and Barry 2010), there is circumstantial evidence of a drastic reduction in the disease mainly as a result of change in the water ecology from the fast flowing riverine system, which provided a suitable environment for the vector *Simulium damnosum*, to a slow flowing system after the dam, which was not suitable for vector development. In addition, the 20-year Onchocerciasis Eradication Programme, which started in March 1974, achieved much success. The discovery of Ivermectin for mass treatment also significantly impacted on the prevalence of onchocerciasis in the Volta Basin.

While onchoceriasis reduced with the construction of the dam, schistosomiasis or bilharzia increased in prevalence. The change in the river system to a slow flowing river with the bloom in aquatic vegetation such as *Ceratophylum* sp. supported the proliferation of the snail vector that transmitted the *Schistosoma* parasite. Prevalence in school children was 5% according to an epidemiological survey made in 1960–61 before the lake was formed. By 1979, urinary schistosomiasis had become the most prevalent disease in the area, affecting some 75% of lakeside residents. Today, both the intestinal and, particularly, urinary forms of the disease are prevalent in the Volta Basin of Ghana. Intestinal schistosomiasis is common in the estuarine communities below the Akosombo dam, whereas urinary schistosomiasis is widespread in the whole Volta Basin. Recent studies have also found 10.6% of women in the Lower Volta Basin of Ghana to have genital schistosomiasis (Mahama et al. 2005) (Figure 9).

Trypnosomiasis is a disease caused by the parasite *Trypanosoma*, which affects humans and animals. Among humans it is known to cause the disease known as sleeping sickness. Human trypanosomiasis was prevalent along the Volta River as the forests, preimpoundment era, provided a habitat for the vector *Glossina* sp. (testse fly). The formation of the lake was,

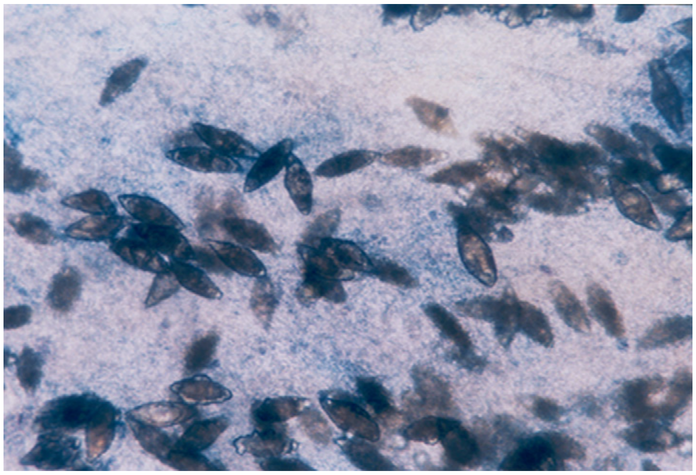

Figure 9 *Schistosoma haematobium* ova in cervical tissue. Source: Yirenya-Tawiah.

however, beneficial in the control of this disease as it drowned the large area of forest that habored the tsetsefly (World Bank 2010). Since 1973, no new cases have been recorded around the lake.

Bovine trypansomiasis, however, continues to be endemic in the northern portion of the Volta Basin in Ghana. A longitudinal study conducted along the White Volta and its tributaries showed the predominance of *Trypanosoma vivax* in tsetseflies captured from their study area (Osório et al. 2008). The effects of bovine typanosomiasis include loss in beef, milk, and leather production (Smithsonian Report 1974).

5.19.9.2 Environmental Changes in the Volta Basin

5.19.9.2.1 Aquatic Weeds

Preliminary studies conducted preimpoundment of the Volta River indicated many aquatic weeds to be present in the basin, but well-known aggressive forms, e.g., papyrus (*Cyperus papyrus*), water hyacinth (*Eichhornia crasippes*), kariba weeds (*Salvinia molesta*), and alligator weed (*Alternanthera philoxeroides*), were absent (Akrasi 2005). The main riverbed was infiltrated with very few aquatic weeds resulting from annual floods, with most of the aquatic weeds found in the riverine lagoons and other tributaries (Akrasi 2005).

Soon after the damming of the river, the change in ecology began to support the proliferation of aquatic weeds. These include *Pistia*, *Vossia* spp., and *Ceratophyllum*. This created suitable habitats for fish, whereas the ceratophyllum's submerged beds house large populations of *Bulinus* snails that habor the *Schistosoma* parasites. In recent times, there has been the invasion of water hyacinth in the Volta Lake and Lower Volta River channel right down to the estuary. This, coupled with the effects of climatic change, provides a big threat to the reduction of the basin size because of its aggressive nature of spread (**Figure 10**).

5.19.9.2.2 Sediment Changes

Sedimentation is recognized as a potential problem in Volta Lake, both in terms of loss of water storage capacity and role of sediment-associated nutrients and contaminants in degrading its water quality and aquatic ecosystems. However, assessment of potential sediment problems is hindered by limited information on the magnitude of the suspended sediment fluxes entering the lake from its numerous tributaries and the overall sediment input to the lake basin. The Volta River Engineering Report indicated from preimpoundment studies that the capacity of the reservoir was such that "no measurable reduction due to siltation could take place in the lake for several hundreds of years" (Akrasi 2005). Before the construction of the Akosombo dam, the highest measurements of suspended sediment concentration of the Volta River at Ajena in 1956, at the height of the flood season, did not exceed 90 mg l^{-1} near the surface (Akrasi 2005).

Akrasi (2005) indicated that the suspended sediment concentrations observed were relatively insensitive to an increase in the discharge. In the case of the Afram River at Aframso, the exponent of the sediment load discharge relationship is <1.0, indicating that the concentrations tend to decrease when the discharges increase. The exponent values according to Akrasi (2005) are substantially lower than the typical values between 2.0 and 3.0, as cited by Gregory and Walling (1973). These low exponent values suggest that the rivers remain turbid over a wide range of flows, and the suspended sediment concentrations remain relatively high during low flows. This situation could also reflect the relatively low gradient of the river system and the importance of localized storms in generating local sediment inputs to the river system, which are essentially unrelated to the overall water discharge regime. Overall, Akrasi (2005) estimated the mean annual suspended sediment input into Lake Volta to be $\approx 17 \times 10^6$ t year^{-1}, which is equivalent to a mean annual specific suspended sediment yield of 52 t km^{-2} year^{-1}.

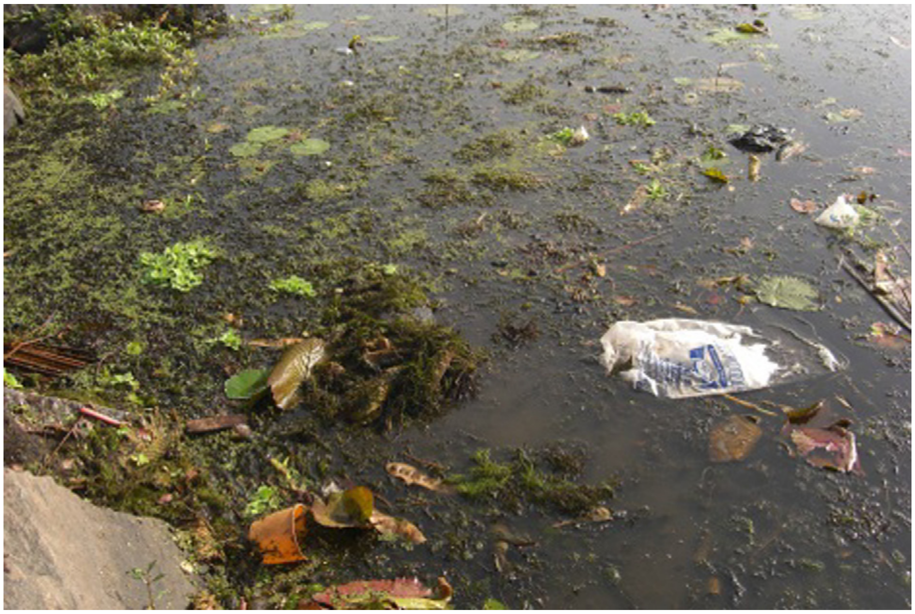

Figure 10 Proliferation of the Kpong Headpond with *Ceratophyllum damnosum*. Photograph by Dzidzo Yirenya-Tawiah.

Although the observed sedimentation rates are still low, continuous monitoring of sedimentation is necessary, as there is intensive erosion leading to siltation and sedimentation of the river channel due to deforestation as a result of activities of people living in uncontrolled human settlements.

5.19.9.2.3 Channel Morphology (Sandbars)

Some morphological changes have occurred along the stretch of the Volta River, particularly downstream of the river at Akuse and in its delta zone. Since 1974, the point at which the Volta entered the sea is known to have shifted 12 km eastwards in a channel, which runs parallel to the coast (Obuobie and Barry 2010). This phenomenon of gradual eastward shift of the mouth of the Volta River has been known in the past, but the process seems to have been accelerated since the construction of the Akosombo dam and the flood flushing of the river mouth stopped. Subsequently, the changes that have occurred in the delta zone with its potential disastrous effect on estuarine communities from any rapid floods have prompted the VRA to artificially reestablish a direct flow into the sea through dredging. Channel morphological changes are also probably linked to accelerated coastal erosion at Ada. Before dam construction, seasonal floods flushed out sandbars, which might have started during the dry season; thus, the estuary was largely kept free of sandbars. However, after the construction of the dam, because of the absence of annual floods, sandbars gradually formed at the estuary and in time virtually blocked inflows from the river to the sea (Figure 11).

5.19.9.2.4 Deforestation

The Volta River Basin in Ghana is one of the areas experiencing rapid deforestation in West Africa. The vegetation in the basin is characterized by SDF, savanna, and woodland types (Gregory and Walling 1973). Predictions show that about 20 and 25% of all sub-basins within the Black Volta and Daka sub-basins, respectively, would experience deforestation as a result of an increase in population (Kumi 1973). In the Lower Volta Basin, the Afram plains and other areas in the south have been the focus of increasing settlement and agricultural development since the 1960s. The forest and transitional areas are intensively farmed with cocoa, coffee, plantain, cocoyam, cassava, oil palm, and maize on small bush fallow plots. A large modern commercial farm at Ejura specializes in maize production. Some timber extraction also takes place in these areas, and the area serves as a major source of fuel wood for charcoal making.

The VRA has taken serious measures to avoid eventual silting of the lake. The authority has sponsored two afforestation projects intended to stop erosion around the lake. In the Adjena Gorge, VRA and the Forestry Department have declared the steep areas bordering the lake as protected lands. VRA also funded another pilot afforestation project in the low slope areas around Yeji in the Brong Ahafo region. The objective of this project is to encourage fishermen to plant wood lots and adopt the use of improved stoves, which use less fuel wood for fish smoking. It is hoped that this project would help to restore some 580 ha of tree cover and reduce the dependency on fuel wood by 60 % in the Yeji area.

5.19.9.2.5 Seismicity

Historically, most parts of Ghana are seismically stable but for the triangle extending southeastward from the Togo quartzite, or roughly from a line joining the cities of Accra and Ho. Initial assessment of lake seismicity revealed that the creation of the lake would add extra weight to the underlying rocks to the tune of 165 million metric tons when the lake reaches its estimated capacity of 165 km^3. The significance of this on seismic activity was, however, not known since the necessary seismic measurements were not made during the filling of the lake.

In November 1964, when about 28 km^3 of water had been impounded, an earthquake of intensity of five on the modified Mercalli scale occurred with its epicenter located near Koforidua, about 40 km south of the reservoir. In December 1966, another earthquake occurred when the total impoundment stood at 102 km^3, and a third occurred in February 1969

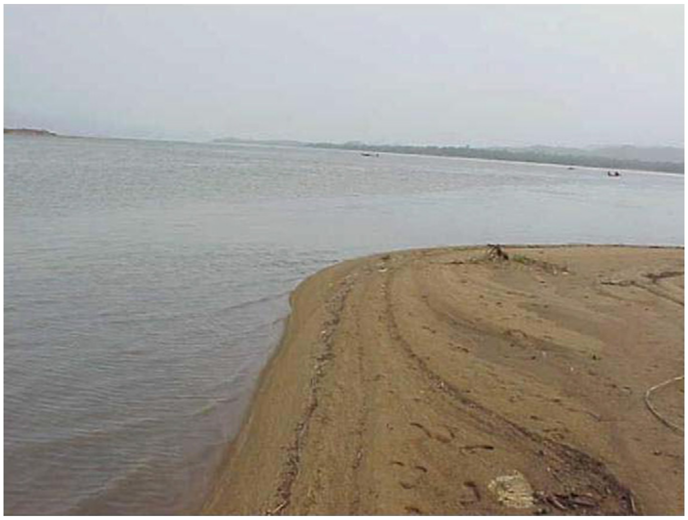

Figure 11 Sandbar on the Volta River mouth.

with storage at 162 km^3, but the epicenters for these shocks were offshore from Accra and more remote from the lake (Obuobie and Barry 2010). These incidents led Kumi (1973) to conclude that at least the 1964 incident, which had its epicenter within 40 km of the reservoir, could be attributed to crustal readjustments associated with the initial stages of the lake's infilling. Earthquake-triggering effects include change in pressure, change in weight, and vibrations.

5.19.9.2.6 Microclimatic Changes

Expected significant microclimatic changes due to transformation of bare or vegetated land into a water body was predicted during Volta Lake formation. In addition, it was also anticipated that the creation of the Volta Lake would increase atmospheric moisture by making more water available for evaporation. Oral accounts of sudden changes in wind speed on the Volta Lake and surrounding areas have been documented by Moxon (1984). Similar reports of observed changes in local weather conditions were corroborated by the residents during field survey of the impact of water projects in Ghana by the personnel of Water Resources Research Institute (De-Heer Amissah 1969). On the other hand, a study on the impact of the Volta Lake on the local climate in Tamale and Kete Krachi in the north and Akuse and Accra in the south, 2 years after the filling of the lake, by De-Heer Amissah (1969) found no significant changes in the monthly rainfall amounts at the four stations, even though a tendency toward decreasing rainfall amounts at Kete Krachi and increasing amounts at Tamale was becoming evident. The mean monthly maximum temperature since 1964 at Kete Krachi seemed to be lower than the pre-project 10-year mean, whereas the minimum temperatures were higher than the 10-year mean. Work by Opoku-Ankomah (1996) on the rainfall pattern of Accra from 1935 to 1995 divided into decades, i.e., 1936–45, 1946–55, etc., showed that there was a gradual rise of total rainfall from the beginning of 1936–45 to the 1956–65 decade and a decline thereafter till 1986–95.

5.19.10 Conclusion

The Volta River Basin is one of the largest river systems in West Africa, and the water resources of the basin are important for consumptive use, i.e., domestic and industrial water supply, crop irrigation and livestock watering, as well as for nonconsumptive use, which includes hydropower generation, fisheries, recreation, and tourism. The status of communities within the Volta Basin is affected by the type of economic activity available (mainly agriculture and fisheries), the degree of water insecurity (which affects access to safe drinking water and water-related diseases), as well as environmental impacts of upstream activities. High population growth rates and associated impacts of reduced land cover and deforestation, coupled with global climatic change, are affecting the ecological condition of the Volta River Basin. Increased agricultural production systems have led to the degradation and overexploitation of terrestrial and aquatic natural resources. There has also been an increase in the number of large and small dams as a consequence of rising numbers in settlements in Ghana, Benin, and Burkina Faso. The construction of these dams has caused contamination, reduced water storage capacity, and loss of aquatic ecosystems as a result of increased sedimentation, invasive aquatic species, increased proliferation of aquatic weeds, and downstream changes to the delta zone that affect estuarine processes and cause coastal erosion.

With the rising trend of prolonged dry seasons and flooding events due to excessive rainfall, the basin is experiencing a growing scarcity in water resources. A number of climate models and the comparisons of various scenarios with different assumptions have projected a decrease in rainfall of 25–30% (Jung 2006), an overall slight increase in total yearly rainfall with strong spatial and temporal heterogeneity (Kasei 2009; Kunstmann and Jung 2005), or reduced flows during the dry season and increased flows in the rainy season (Laube et al. 2008). Other studies have reported a 17% increase in surface runoff resulting in higher discharge (Kasei 2009) or 29% increase in subsurface flow leading to 33% increase in discharge (Obuobie 2008) by 2039. However, it is important to recognize that, at best, these model predictions only include a subset of possible temperature and precipitation conditions in the coming decades (Pielke et al. 2012).

Nevertheless, to reduce risk, there should be the development of a more resilient system, if there is an overall increase in seasonal river flow variability in the Volta Basin (Paeth et al. 2005; Pielke et al. 2011). With increases in the frequencies of extreme drought and flood events, there would be impacts on agriculture and food security in addition to further deterioration in water quality, reduced hydropower generation, and spread of water-borne diseases such as malaria, onchocerciasis, and schistosomiasis/bilharzia. Future actions to manage the Volta Basin should incorporate population growth and development demand on resources by all countries within the Volta Basin. With the uncertainties in long-term changes in climate statistics and short-term variability, focus should be placed on improving the ability to manage future possibilities by reducing the current vulnerability of the society and communities to climatic variability and extreme events, improving and updating management options to deal with the worst-case scenarios and taking advantage of possible opportunities. Implementation of various adaptation measures, such as water conservation, reduction in water demand and use, new strategies for drought- and flood-resistant farming, and the application of appropriate and pragmatic management practices, will all contribute to the reduction in the impacts of climate on water resources.

Within the Volta Basin, a number of institutions are responsible for managing water and soil resources, which has resulted in the overlapping of responsibilities and poor coordination. In order for the management of water and soil resources to be effective, it should be integrated at the local and national level, with emphasis on intersectoral coordination. Management strategies in place are also not effectively enforced as the governance of the basin is currently afflicted by insufficient political support, lack of financial resources, gaps in information, insufficient stakeholder participation, and poor institutional coordination and collaboration. There is the need to address these inherent challenges as well as recognize the advantages and opportunities of effective management of the Volta Basin in sustainable development, adaptation, and energy technologies. Further developments within the basin should not be based on short-term income generation but include long-term sustainability. There is the need for further research to improve the knowledge base for effective integrated management of the transboundary resources in order to optimize activities, including the management of dams, and restore livelihoods and ecosystems both upstream and downstream. Studies and strategies to address anthropogenic impacts and climate on the Volta Basin should incorporate assessment, sustainable use, development, and management of resources in an integrated way.

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5.20 Assessment of the Vulnerabilities of the Nubian Sandstone Fossil Aquifer, North Africa

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Glossary

Fossil aquifers Aquifers that were recharged during previous wet climatic periods and are receiving negligible modern recharge.

Paleo-recharge Recharge that occurred during previous wet climatic periods.

Autochthonous recharge Recharge resulting from the infiltration of precipitation over the aquifer outcrops.

5.20.1 Introduction

Many of the arid and hyperarid parts of the world are blessed by having large amounts of potable fresh water stored in large extensive (kilometer-thick) aquifers stretching for hundreds to thousands of kilometers across political boundaries; these are largely nonrenewable aquifers, commonly referred to as 'fossil' aquifers, with little or no modern recharge. They were largely recharged under previous wet climatic periods. These aquifers are extremely important to the general population of these countries given the prevailing arid conditions and the growing need for fresh water supply arising from a general trend of increasing population. The aquifers are vulnerable to pollution, unsustainable overexploitation, and disputes over transnational boundary issues. However, despite their importance to the sustenance of the population of the arid world, the majority of these aquifers remain poorly investigated. Possible causes include their locations in less-developed parts of the world, the general inaccessibility of many of these areas, difficulties in collecting background information, and the unavailability of local funding and expertise to support research in these areas. As a consequence, our current understanding of the fossil groundwater systems in many of the arid and hyperarid parts of the world is lacking in many respects. Specifically, the following elements remain poorly constrained: (1) nature and causes of spatial and temporal mass variations and the extent to which these aquifers are being depleted, (2) timing

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and mechanisms of modern and paleo-recharge, (3) locations and amount of discharge, (4) movements of deeper circulating groundwater in these systems on a regional scale, and (5) the hydraulic connectivity of subbasins within the aquifer. We address these important issues in one of the largest fossil groundwater systems in the world, the Nubian Aquifer System of northeast Africa. We apply an integrated approach for data collection, analysis, and distribution that addresses the difficulties cited above and leads to the development of realistic conceptual and groundwater flow models and sustainable management scenarios for these aquifers. Such models are urgently needed to protect the precious groundwater resources from pollution, overexploitation, and disputes over water rights near international boundaries. In addition, the models should assess the predictability of the hydrologic effects associated with climate variability and longer term change.

5.20.2 Geologic and Hydrologic Setting of the Nubian Aquifer System

Beneath the surface of the hyperarid Western Desert of Egypt and adjacent portions of eastern Libya, northeastern Chad, and northwestern Sudan (Figure 1) lies an immense reservoir (150 000 km^3) of fresh groundwater in the Nubian Aquifer System (Thorweihe and Heinl 2002). This precious resource is largely a fossil groundwater reservoir with minor recharge compared to the discharge. It contains the equivalent of more than 500 years of Nile River discharge (Thorweihe and Heinl 2002). The Nubian Aquifer System has two major basins: (1) the Kufra Basin of Libya, northeastern Chad, and northwestern Sudan, and (2) the Dakhla Basin of Egypt (Figure 1). Water in the Kufra basin flows from the south to north and in the Dakhla Basin from the south-southwest to north-northeast (average gradient $\sim 0.5\,\mathrm{m\,km^{-1}}$) and naturally discharges at oases (Thorweihe and Heinl 2002).

The area of the Nubian Aquifer System is about 2 000 000 km^2. The aquifer mainly consists of continental sandstones with intercalated shales of shallow marine and deltaic origin of the pre-Upper Cretaceous age, unconformably overlying Proterozoic basement. The aquifer reaches a thickness approaching 4000 m in the deepest parts of the basin (Thorweihe and Heinl 2002). The sandstone is exposed in northeast Chad, southeast Libya, northern Sudan, and southwest Egypt. North of the 25th parallel in Egypt, the Nubian Aquifer is confined beneath thick marine shales of the Upper Cretaceous age. North of the 29th parallel, northward groundwater flow is limited by saline water. Where the aquifer is confined, it is divided into four thick (tens to hundreds of meters thick) horizons of sandstone layers that are separated by relatively thin (meters to tens of meters thick) shale layers. These horizons are commonly referred to as zones A, B, C, and D, where A is the shallowest and D is the deepest. Despite the large variations in thickness of each of these zones, they are readily correlated over extensive areas in the Western Desert of Egypt from electric and radioactivity well-logging records (Thorweihe 1982).

Water in the Nubian Aquifer naturally discharges in oasis areas. Since large-scale extraction began in the 1960s, water levels have substantially decreased in these areas, especially in western Egypt and Libya. Water quality throughout the Nubian Aquifer is generally good, and it is viable as a drinking-water source and for irrigation with little or no pretreatment. Particular concerns regarding the protection of the aquifer's water quality are related to domestic and industrial wastewater treatment and solid waste management practices in water extraction zones. The level of natural radioactivity in the Nubian Aquifer water has not yet been well characterized, but studies of equivalent water in Jordan have shown high levels of radium (Vengosh et al. 2009).

5.20.3 Origin and Evolution of the Nubian Aquifer System

Two models have been proposed to explain the origin of the waters of the Nubian Aquifer: (1) large-scale flow from mountainous recharge areas in Chad (Ball 1927, Sanford 1935), and (2) autochthonous recharge during more humid climatic conditions that previously prevailed throughout the present desert area (Sultan et al. 1997, Thorweihe 1982). The former hypothesis is supported by the regional gradient in groundwater surface in Egypt, Libya, Chad, and Sudan; highest in the southwest and lowest in the northeast. The latter model is partly supported by the stable isotopic and age data for the Nubian groundwater in the Western Desert of Egypt that range from thousands to hundreds of thousands of years (Sturchio et al. 2004, Patterson et al. 2005).

There are several problems with both models. The large-scale flow model (hypothesis 1) is inconsistent with recent findings (Sturchio et al. 2004, Patterson et al. 2005) that show a progression of groundwater ages (^{81}Kr, ^{36}Cl) within the Dakhla basin from southwest (East Uweinat: <30 kyr) to northeast (Bauti-1: 1000 kyr), which suggest that autochthonous recharge of deep groundwater in Egypt primarily occurred at the foothills of the Uweinat mountain range (Gebel Uweinat) and not in Chad (Ennedi Plateau), as previously advocated by the large-scale flow models (Figures 1 and 2). We show that the autochthonous recharge within the Dakhla basin is further corroborated by the apparent presence of major paleodrainage networks in the extensive Nubian Sandstone outcrops, the network extending from the foothills of the Uweinat mountains toward the River Nile. Although the observed paleodrainage patterns could have resulted from massive groundwater discharge during previous wet climatic periods, a more likely interpretation is that they represent paleo-recharge areas. The relatively young ages of the groundwater in the postulated recharge areas support the latter interpretation (Froehlich et al. 2007). Simply put, it would take much more than 30 kyr (the age of groundwater in East Uweinat) for the groundwater to travel from Chad to the vicinity of east Uweinat.

The autochthonous recharge concept (hypothesis 2) is inconsistent with the reported (Ball 1927) hydraulic gradient (from southwest to northeast) and the expected flow given the large transmissivity of the Nubian Sandstone. With more and more wells being drilled across the Nubian Aquifer, it is becoming clear that the original distribution of head data was oversimplified given the paucity of well data at the time and that recharge is probably occurring at the foothills of the highlands in Chad and in other areas as well (e.g., Gebel

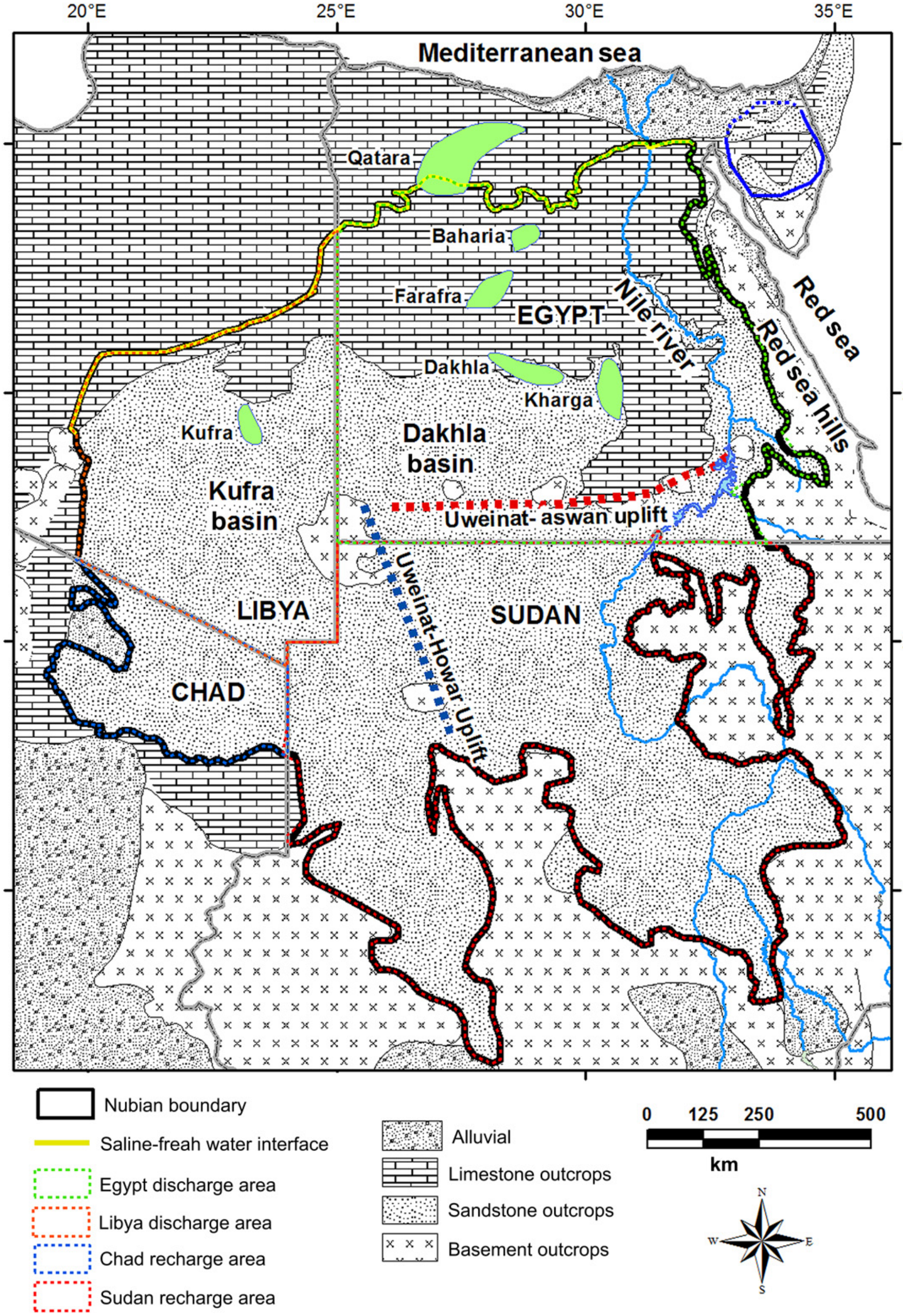

20°E
25°E
30°E
35°E
30°N
25°N
20°N
15°N
Mediterranean sea
Qatara
Baharia
Farafra
Dakhla
Kharga
EGYPT
Nile river
Red sea
Red sea hills
Kufra
Dakhla basin
Kufra basin
Uweinat- aswan uplift
LIBYA
SUDAN
Uweinat-Howar Uplift
CHAD
Nubian boundary
Saline-freah water interface
Egypt discharge area
Libya discharge area
Chad recharge area
Sudan recharge area
Alluvial
Limestone outcrops
Sandstone outcrops
Basement outcrops
0 125 250 500
km
N
W
E
S

Figure 1 Distribution of the Nubian Aquifer in Egypt, Sudan, Chad, and Libya; Nubian outcrops; and basement uplifts (red and blue dashed lines). The aquifer is bound by basement outcrops from the east, west, and south and by the saline/freshwater interface in the north (yellow line). The areal extent of the Nubian Aquifer in Sinai (blue outline) and the areas of recharge (in Chad and Sudan) and discharge (Egypt and Libya) that were examined using GRACE temporal data are also shown.

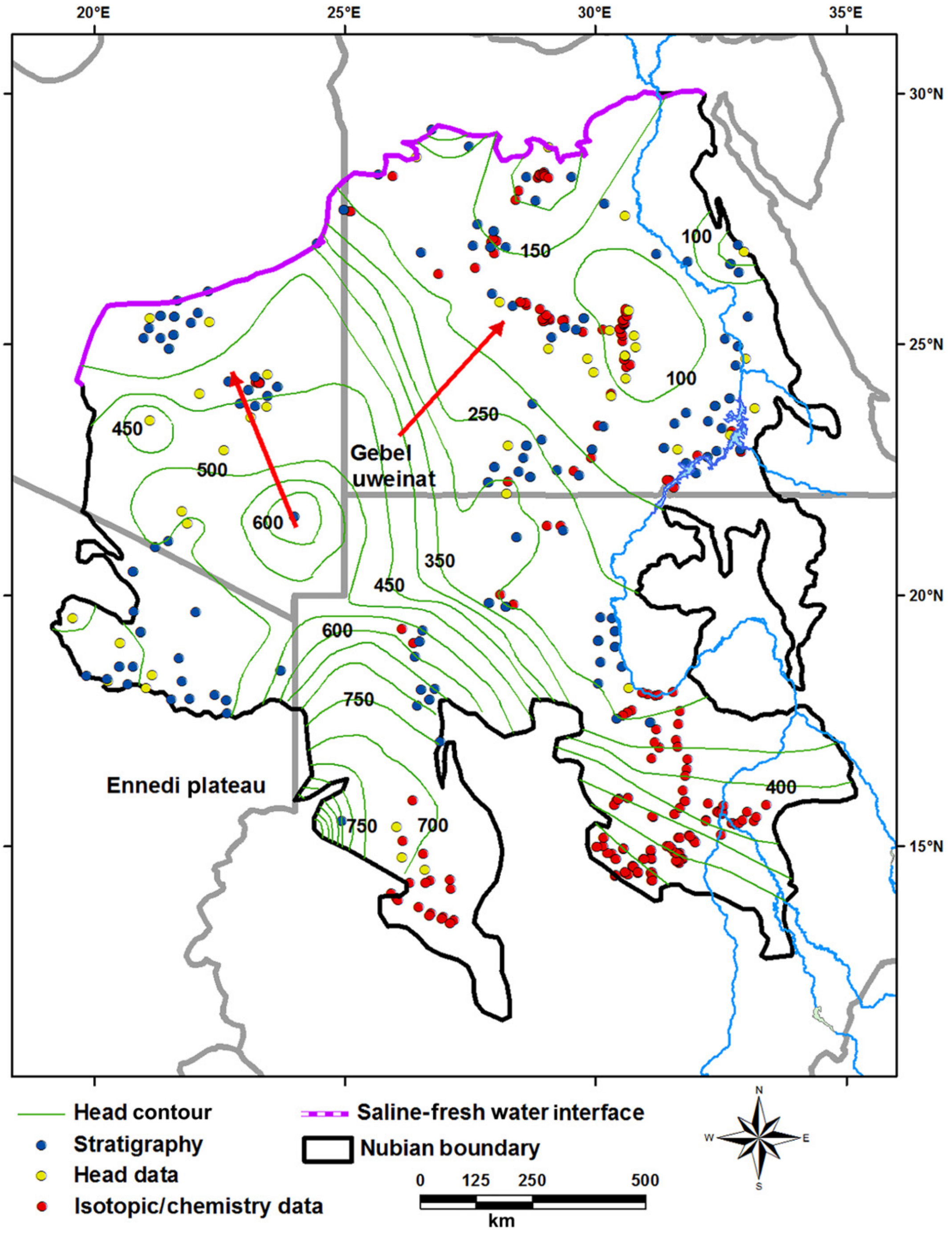

20°E
25°E
30°E
35°E
30°N
25°N
20°N
15°N
100
150
100
250
450
500
600
Gebel uweinat
350
450
600
750
Ennedi plateau
750
700
400
Head contour
Stratigraphy
Head data
Isotopic/chemistry data
Saline-fresh water interface
Nubian boundary
0 125 250 500
km
N
W
E
S

Figure 2 Initial potentiometric map and available well data; yellow—head data; red—isotopic and geochemical data; and blue—stratigraphic data. Also shown are regional groundwater flow directions (red arrow).

Uweinat). Figure 2 is an initial potentiometric map of the Nubian Aquifer System that we generated from initial head data extracted from wells (yellow dots in Figure 2) in Egypt, Sudan, Libya, and Chad (CEDARE 2001).

Both models assume that the Nubian Aquifer was entirely recharged in previous wet climatic periods and are thus at odds with meteorological data and with inferences made from radiocarbon and stable isotopic data which indicate that the Nubian Aquifer is being locally recharged by modern water in some areas. Considerable precipitation ($>150\,\mathrm{mm\,yr^{-1}}$) (Legates and Wilmott 1997, Nicholson 1997) occurs over the recharge areas where the Nubian Aquifer crops out in central Sudan and in northeast Chad. Published isotopic and geochronologic data indicate that in northern Sudan and in southwest Egypt (areas closer to the recharge domains), radiocarbon ages for Nubian Aquifer waters are relatively young and that oxygen and hydrogen isotopic compositions are enriched compared to those of groundwater to the north (Hesse et al. 1987; Thorweihe 1990; Froehlich et al. 2007), possibly indicating mixing between fossil groundwater and modern precipitation in recharge areas to the south. Using the Sinai Peninsula as a test site and adopting integrated methodologies, we have shown that the Nubian Aquifer is receiving modern recharge in areas of relatively high precipitation (Sultan et al. 2011).

As previously described, there are four stratigraphic zones within the Nubian Aquifer in the Western Desert of Egypt that are believed to be hydraulically interconnected over large segments of the Western Desert (Brinkmann et al. 1987). This understanding might not be the case where uplifts (e.g., Uweinat-Aswan, Uweinat-Howar, **Figure 1**) could restrict flow from one part of the aquifer to another. Geochronologic and isotopic data show that the Uweinat-Aswan uplift restricts groundwater flow and we emphasize the importance of understanding the role of these uplifts across the aquifer as an important step toward the development of sound conceptual models and the construction of realistic groundwater flow models. To the best of our knowledge, the existing Nubian Aquifer models (e.g., Brinkmann et al. 1987; Euroconsult-Pacer 1983; Soliman et al. 1998) treat the aquifer as being hydraulically interconnected across its entire spatial extent. Newer data indicate the complexity of the Nubian Aquifer System and show the need for the re-evaluation of the existing models for the origin and evolution of the Nubian Aquifer groundwater.

5.20.4 Temporal and Spatial Mass Variations across the Nubian Aquifer Using GRACE Data

To date, there are no reliable estimates for the temporal and spatial variations in discharge (natural and manmade) and recharge across the Nubian Aquifer, nor is there an adequate understanding of the connectivity of the various subbasins within the Nubian Aquifer. This is largely due to the large areal extent of the aquifer and the paucity of field data on a regional scale, a situation that is hindering the development of sustainable management schemes for this valuable resource. We address this problem by first examining temporal and spatial mass variations across the investigated areas extracted from satellite temporal gravity measurements from GRACE to identify areas within the aquifer that are showing signs of declining water supplies. Then we propose various solutions that can allow for sustainable utilization of this valuable resource.

5.20.4.1 Processing of GRACE Data

The GRACE satellite mission was launched in March 2002 to map the temporal variations in the Earth's global gravity field on a monthly basis (Tapley et al. 2004). Variations in the Earth's gravity field are caused by changes in the Earth's mass distribution. Almost all of the variability that occurs on the relatively short time scales accessible with GRACE (i.e., seasonal to interannual) is due to mass variations at or near the Earth's surface. Generally, the largest time-variable gravity signals observable in GRACE data come from changes in the distribution of water and snow stored on land (Wahr et al. 1998).

Because GRACE provides measurements that average over large areas, it is well suited for examining hydrologic processes in the Nubian Aquifer, one of the world's largest aquifers in both areal distribution and storage capacity. The hydrologic setting of the Nubian Aquifer provides opportunities to investigate a wide range of hydrologic issues of worldwide relevance, including the magnitude of recharge, discharge, and the role the uplifts might play as barriers to groundwater flow. Discharge is primarily concentrated in the northern areas in Libya, and in Egypt this occurs both in natural depressions and in areas where major water extraction projects are underway, whereas recharge and infiltration are primarily concentrated in the southern portions of the aquifer area where most precipitation occurs. The provenance in the distribution of the recharge and discharge areas in the Nubian Aquifer alleviates complexities that might be encountered in studying similar systems in temperate areas with concurrent recharge and discharge, which could render the interpretation of GRACE data more difficult.

We used the University of Texas Center for Space Research Release-4 (UT-CSR RL04) GRACE gravity field solutions that span the period from April 2002 through November 2010 (101 months). The UT-CSR RL04 gravity field solutions were processed using procedures described in Ahmed et al. 2011. The temporal mean was removed, a destriping filter was applied, destriped solutions were smoothed using a Gaussian function (250 km radius), and the results were converted into surface mass values (in units of equivalent water thickness) on a 0.5×0.5 degree grid. To obtain results for an individual discharge area (see below), we averaged together the results for every grid point lying within that area. All GRACE-derived mass fields were interpreted as reflecting changes in water storage, given: (1) the slow rates of the mass variations in the underlying solid Earth, (2) an absence of large earthquakes and glacial isostatic adjustment in the region, (3) the small to negligible contributions related to mass fluctuations from the adjacent ocean (Wahr et al. 1998) and the corrections applied to remove the time-variable oceanic gravity signal from raw GRACE measurements (Tapley et al. 2004), and (4) the fact that errors in the atmospheric pressure corrections applied to GRACE data are likely to be negligible in this region (Velicogna et al. 2001).

5.20.4.2 Seasonal and Annual Trends in Libya, Egypt, Sudan, and Chad

Time-series analyses for the GRACE monthly gravity solutions show seasonal patterns and interannual trends (**Figure. 3**). Positive interannual trends are interpreted here to indicate increasing water storage probably due to enhanced recharge, and negative trends indicate decreasing water storage probably due to excessive water extraction and natural discharge. Changing volumes of water impounded in artificial lakes behind dams can also give rise to positive or negative interannual trends on local scales.

Examination of the GRACE time series over discharge areas in the Nubian Aquifer in Egypt and eastern Libya shows a seasonal cycle with highs in the months of June to August and lows in the months of December to February (**Figures 3(a) and 3(b)**). We suspect that these patterns are largely

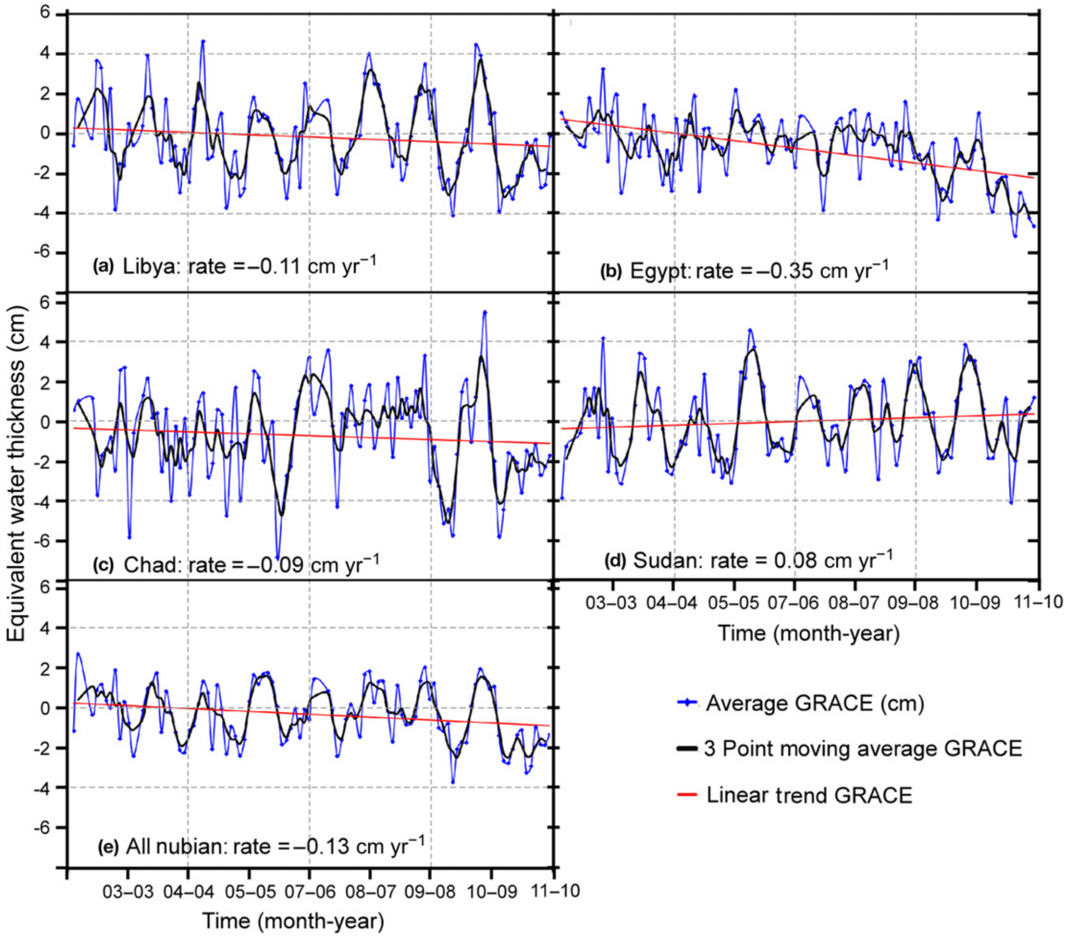


Figure 3 Time-series analysis for the GRACE monthly gravity solutions showing seasonal patterns, and/or interannual trends for areas of discharge in Libya (a) and Egypt (b), as well as recharge in Chad (c), Sudan (d), and the entire Nubian Aquifer (e). Also shown are the best fit linear trend line for each of these data sets; regression trend lines are significant at 99% and 95% levels of confidence for Egypt (b) and for the entire area of the Nubian Aquifer (e), respectively. Linear trends for areas cited as showing steady to near-steady conditions are significant at lower levels of confidence (level of confidence: Libya 80%; Sudan 71%; Chad 63%).

related to the uneven patterns of extraction throughout the year. Because most of the water extracted from the Nubian Aquifer is used for agricultural purposes that largely occur throughout the winter season, the maximum losses in mass are observed during this time period. In the summer, the extracted water is replenished to a large extent by inflow of groundwater. If this is true, the average annual extraction could be estimated from the observed temporal trends in the product of the area of the Nubian Aquifer and difference between the water thickness in the summer and winter seasons averaged over the investigated period. We also observe an interannual progressive depletion amounting to $-2.35 \times 10^9\,\mathrm{m}^3\,\mathrm{yr}^{-1}$ ($-3.5\,\mathrm{mm\,yr}^{-1}$) in Egypt, and $-0.39 \times 10^9\,\mathrm{m}^3\,\mathrm{yr}^{-1}$ ($-1.1\,\mathrm{mm\,yr}^{-1}$) in Libya. It is noteworthy that the overall decline over the entire Nubian Aquifer System ($-2.65 \times 10^9\,\mathrm{m}^3\,\mathrm{yr}^{-1}$; $-1.3\,\mathrm{mm\,yr}^{-1}$) could be largely accounted for by the mass depletions over Egypt. These depletions are probably related to a progressive increase in extraction rates with time in these areas that exceed replenishment by groundwater flow from neighboring locations. Progressive water extraction programs were initiated in the 1960s to use the Nubian Aquifer water for irrigation and drinking purposes in Egypt and in Libya (Salem et al. 2002). Extraction from aquifers other than the Nubian Aquifer is negligible; the Nubian Aquifer is the most extensive in area and dimension of all aquifers in Egypt and in Libya, and is by far the most heavily used of all the aquifers (AbuZeid and AbdelMeguid 2006) in these two countries.

The GRACE time series over recharge areas in Chad and Sudan show a seasonal cycle with highs in the months of August and October and lows in the months of May to June, lagging a month or two behind peak precipitation in the area. These seasonal patterns of precipitation and GRACE were accounted for by (Ahmed et al. 2011). They claimed that with the onset of the precipitation period over the recharge areas, a fraction of the water is captured through initial losses, increasing soil moisture, and creating local ponds and sinks; and, thus, increasing the accumulated water and mass. With continued precipitation and mass accumulation, the GRACE results continue to rise; they peak at a point where the soil moisture content approaches saturation. With the decline of precipitation, mass accumulation gradually diminishes to the point at which water received in the soil profile from precipitation is less than that lost to evapo-transpiration and to outflows (runoff, overland flow, interflow, and groundwater flow). This marks a halt to additional increases in water thicknesses and the onset of the effects of mass deficiency. As the rainy season comes to an end, precipitation tapers off and factors such as evaporation, transpiration, and runoff progressively decrease accumulated water, reducing the GRACE response until it bottoms out.

Inspection of Figure 3 shows negligible to small interannual variations in mass with time in Chad ($-0.12 \times 10^9\,\mathrm{m}^3\,\mathrm{yr}^{-1}$; $-0.9\,\mathrm{mm\,yr}^{-1}$) and in Sudan ($0.69 \times 10^9\,\mathrm{m}^3\,\mathrm{yr}^{-1}$; $0.8\,\mathrm{mm\,yr}^{-1}$). We interpret these patterns to indicate steady-state to near-steady-state systems where there are subequal amounts of infiltrating water and water leaving the recharge areas through evapo-transpiration, runoff, and overland and groundwater flow toward the discharge areas in the north. Similar steady-state to near-steady-state conditions are observed over Libya; there, natural and artificial discharge is apparently compensated for by groundwater that can readily flow unobstructed from recharge areas to the south. One explanation for the observed interannual progressive depletion in Egypt is that the east-west trending Uweinat-Aswan uplift is impeding groundwater flow from recharge areas in the south. In the next sections, we attempt to explain the observed mass variations described above by examining modern and paleo-recharge regimes, locations and magnitudes of discharge, and connectivity of subbasins.

5.20.5 Connectivity of Subbasins

A prominent basement uplift within the Dakhla catchment, the Uweinat-Aswan uplift could be traced on the surface by a series of basement outcrops that trend in an east–west direction (Figure 1). The presence of this uplift that is largely formed of basement rocks suggests that the Nubian Aquifer to the north of the uplift is partially disconnected from the Nubian Aquifer to the south of the uplift. This implies that areas to the north of the uplift will experience greater effects of the extraction of groundwater from the Western Desert Oases (Kharga, Dakhla, Farafra, and Baharya).

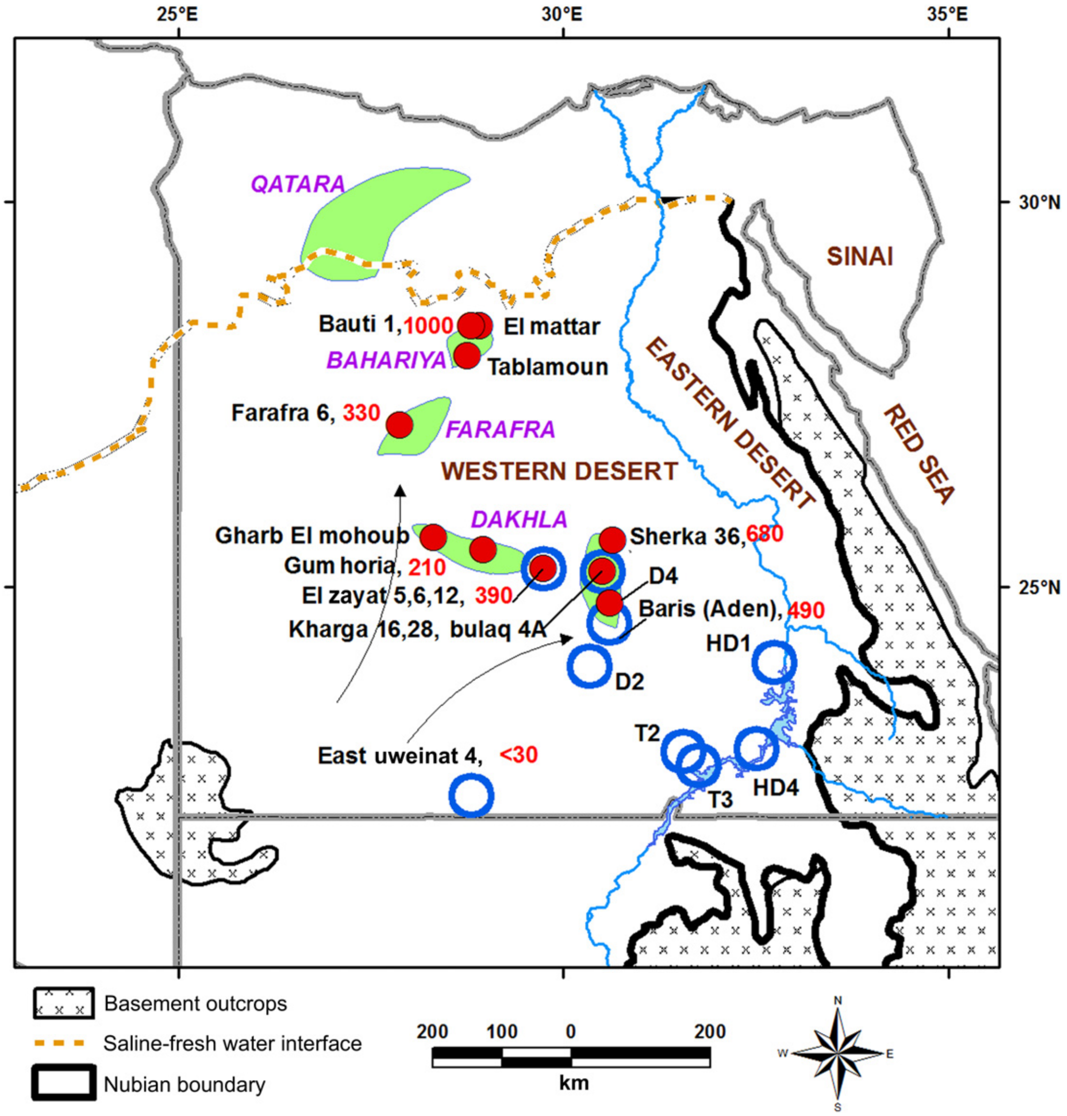
This suggestion is corroborated by the progressive decrease in ages from the northeast to the southwest within the Dakhla basin and by the observed differences in isotopic compositions of groundwater to the north and south of the uplift. The oldest ^{81}Kr age ($\sim$1 million yr) was obtained from Bauti-1 and the youngest ^{36}Cl age (<30 kyr) from East Uweinat (Figure 4) (Sturchio et al. 2004, Patterson et al. 2005). Additional support for this hypothesis comes from comparing the isotopic compositions of groundwater samples north and south of the uplift; samples north of the uplift are isotopically depleted compared to samples south of the uplift. The average isotopic composition for 37 samples to the north of, and proximal (<250 km) to, the Uweinat-Aswan uplift is δ^{18}O: $-10.7‰ \pm 0.9‰$ (Figure 5, solid red dots), whereas that for seven samples to the south of and proximal to the uplift is δ^{18}O: $-8.6‰ \pm 1.4‰$ (Figure 5, solid green dots). Simulations have also shown that the discharge of Lake Nasser into the Nubian Aquifer is impeded by the Aswan Uplift (Kim and Sultan 2002). They concluded that, in their study area, the basement surface forms an impervious lower boundary for the aquifer and acts as a barrier to lateral groundwater flow.

We suggest that GRACE data could potentially be used to gain further insights in the connectivity of subbasins within the Nubian Aquifer that are separated by basement uplifts. If these are restricting groundwater flow, one could expect to observe differences in the seasonal and annual variations across them. Alternatively, there would be no differences if the subbasins are hydraulically well-connected. One measure of the annual and seasonal variations is a standard deviation (SD) image extracted from monthly GRACE solutions (Figure 5). For example, if the east-west trending Uweinat-Aswan uplift is restricting the groundwater flow from the south to the north, one should observe differences in the standard deviation image across the postulated barrier (Figure 5). Examination of GRACE data on either side of the Uweinat-Aswan uplift shows that indeed this is the case (Figures 3(b) and 3(d)), uplift could be impeding groundwater flow from the south.

Throughout the areas occupied by the Nubian Aquifer in neighboring countries there are several other uplifts that could restrict and/or redirect groundwater flow. Examples include the north–south trending Uweinat-Howar uplift in northern Sudan. Because of its north–south trending orientation, this uplift is not restricting the flow of groundwater from the south to the north as is apparently the case with the Uweinat-Aswan uplift. Unfortunately, it is difficult to evaluate the effect of the Uweinat-Howar uplift on groundwater flow because of the absence of reliable residence times, isotopic and geochemical data, and/or groundwater levels and flow directions for the surrounding areas.

5.20.6 Patterns of Paleo-Recharge

Samples of Nubian Aquifer groundwater from wells in the Dakhla basin in the Western Desert of Egypt were measured for ^{81}Kr, ^{36}Cl, and other chemical and isotopic constituents (Figure 4). The range of ages thus derived is <30 kyr–1000 kyr (Sturchio et al. 2004; Patterson et al. 2005). Ages increase from southwest to northeast. This age progression supports flow vectors predicted by numerical hydrodynamic models (Brinkmann et al. 1987), verifying lateral flow of deep groundwater toward the northeast, with recharge of deep groundwater occurring southwest of Dakhla and not in the distant Chad as previously advocated (Figures 1 and 2). ^{81}Kr ages progressively increase with distance to the north and east of Dakhla; their spatial distribution indicates relatively high flow velocities ($\sim 2\,\mathrm{m\,yr}^{-1}$) from the recharge area toward Dakhla and Farafra, and lower velocities ($\sim 0.2\,\mathrm{m\,yr}^{-1}$) from Dakhla toward Kharga and Baris and from Farafra to Bahariya. These observations are consistent with the areal distribution of hydraulically conductive sandstone within the Nubian Aquifer. Southwestward extrapolation of the $\sim 2\,\mathrm{m\,yr}^{-1}$ flow rate inferred from the difference in ages for Dakhla and Farafra is consistent with recharge primarily in the area of the Uweinat uplift near the Egypt–Sudan border, and is inconsistent with models that advocate recharge over mountainous areas farther south in Chad and its surroundings.


25°E
30°E
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25°N
QATARA
SINAI
Bauti 1, 1000
El mattar
BAHARIYA
Tablamoun
Farafra 6, 330
FARAFRA
WESTERN DESERT
EASTERN DESERT
RED SEA
DAKHLA
Gharb El mohoub
Gum horia, 210
El zayat 5,6,12, 390
Kharga 16,28, bulaq 4A
Sherka 36, 680
D4
Baris (Aden), 490
HD1
D2
T2
T3
HD4
East uweinat 4, <30
Basement outcrops
Saline-fresh water interface
Nubian boundary
200 100 0 200
km
N
W
E
S

Figure 4 Locations sampled for ^{81}Kr, ^{36}Cl, and other isotopic measurements. Solid circles represent deep (>200 m) wells; hollow circles represent shallower samples. Red numbers are estimated 81-Kr ages in units of 10^3 yr (from Sultan et al. 2007), except for the age of east Uweinat 4, which is a 36-Cl age estimate (from RIGW, 1993). Also shown are the saline-/freshwater interface (orange line) and outlines of the Nubian Aquifer (thick black line) and river Nile (light blue line). Modified from Patterson, L. J., N. C. Sturchio, B. M. Kennedy, et al. 2005: Cosmogenic, radiogenic, and stable isotopic constraints on groundwater residence time in the Nubian Aquifer, Western Desert of Egypt. *Geochem. Geophys. Geosyst.*, **6**.

We inferred the existence of paleo-recharge areas in the Uweinat uplift area and its surroundings. Paleodrainage channels in Nubian Sandstone bedrock were identified using space-borne radar data that are capable of penetrating the sand sheets (Figure 6(a)). We show that the distribution of drainage networks extracted from satellite-derived digital topography also reflect to a large degree the distribution of underlying paleodrainage systems (now partly buried under sand sheets). Thus, the present topographic drainage networks could be readily used to facilitate mapping the overall distribution of buried paleodrainage networks in areas where radar data are missing. The underlying assumption is that the sand sheet blanket does not obliterate, but rather reflects, the underlying topographic variations. The correspondence between the channel network visible in radar data and that derived from digital topography supports this suggestion.

We defined the drainage channels in the area of the Selima Sand Sheet in Southwestern Egypt using SRTM and ARC/INFO (full-featured geographic information system) watershed delineation routines (ESRI 1991)(Figure 6(b)). The SRTM dataset is a space shuttle-based radar interferometric data set, which provides improved topographic definition in many parts of the world where only low resolution regional scale data previously existed (Farr and Kobrick 2000; Rabus et al. 2003).

Drainage channels, well locations, topographic contours (labeled in meters), vertically exaggerated topography (brightness increasing with elevation), and outcrop areas of Nubian sandstone where the Nubian Aquifer is unconfined and can be

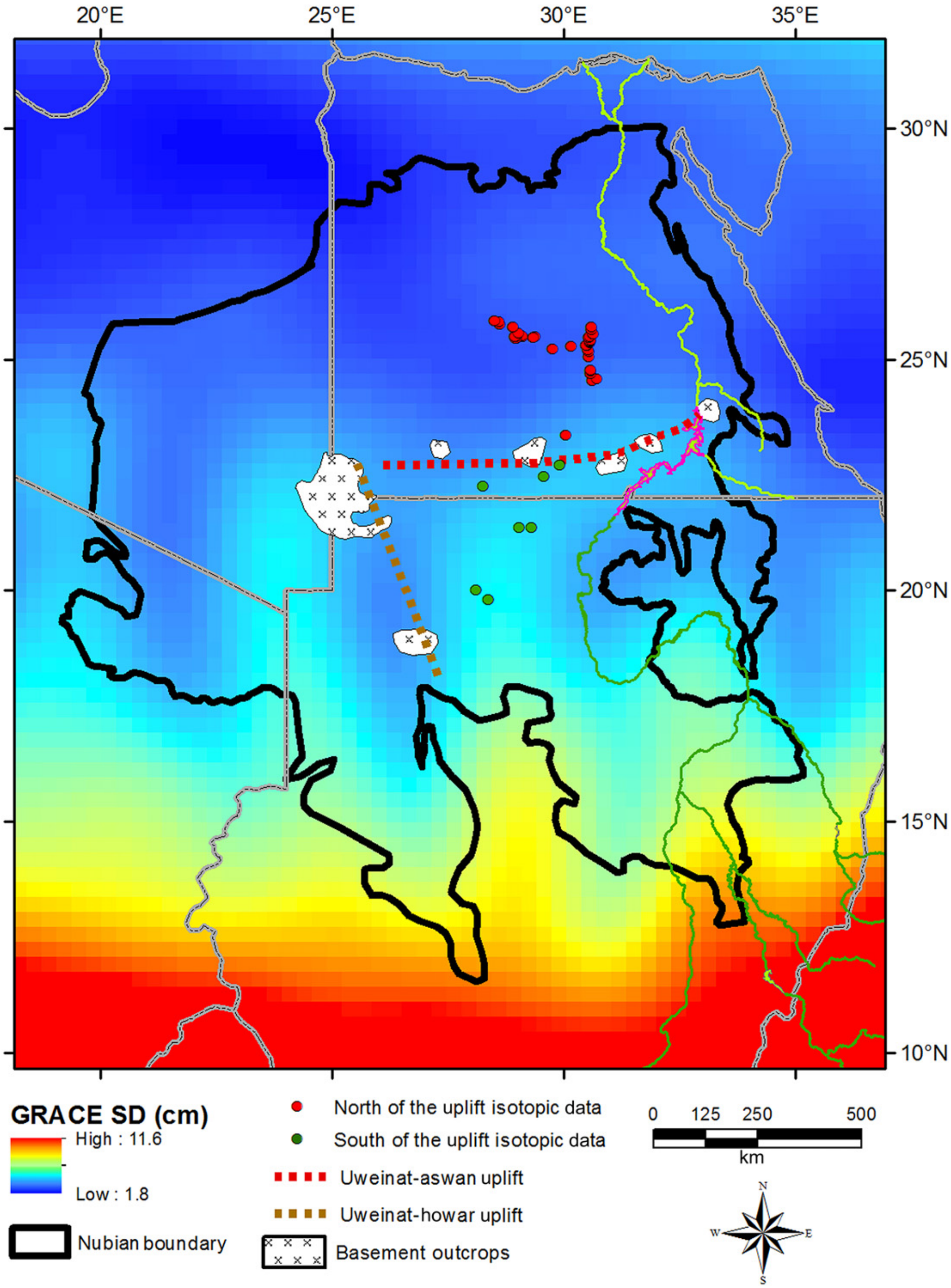

20°E
25°E
30°E
35°E
30°N
25°N
20°N
15°N
10°N
GRACE SD (cm)
High : 11.6
Low : 1.8
Nubian boundary
North of the uplift isotopic data
South of the uplift isotopic data
Uweinat-aswan uplift
Uweinat-howar uplift
Basement outcrops
0 125 250 500
km
N
W
E
S

Figure 5 SD image calculated from GRACE monthly solutions. Also shown are (1) the Uweinat-Aswan uplift and the Uwienat-Howar uplift, and (2) locations for groundwater samples proximal (<250 km from uplift) to the Uweinat-Aswan uplift for which oxygen isotopic compositions were determined.

directly recharged (shaded pale blue) are shown in Figure 6(a). Some well locations depicted in Figure 5 are also shown for reference. Figure 6(a) shows a drainage pattern that extends from southwest to northeast. Within the catchment area, there are two major closed drainage basins (Dakhla, Kharga). In these areas there are thick playa deposits that probably mark the locations of paleolakes that developed in these depressions.

These SRTM-based streams were compared to stream distribution inferred from coregistered SIR-C data (Figure 6(b)). Note the clear correspondence between the SRTM-derived channels and the SIR-C derived channels. Space-borne radar data have been previously used to reveal the distribution of buried drainage channels in the Saharan deserts (Maxwell and Haynes 2001; McCauley et al. 1998; McCauley et al. 1982;

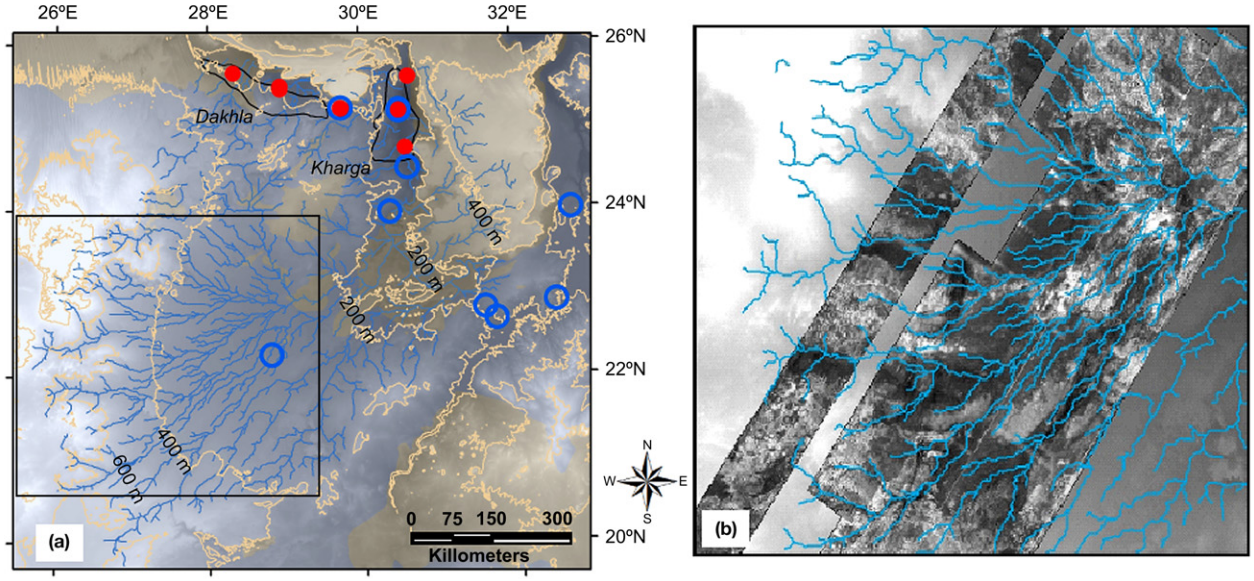


Figure 6 (a) Paleochannels (blue line) in Dakhla basin, derived from SRTM 30 Arc second data. (b) SRTM-derived channels (blue line) overlain onto SIR-C image for the area covered by the box in (a). Also shown are digital elevation contours and groundwater sample locations from Figure 4.

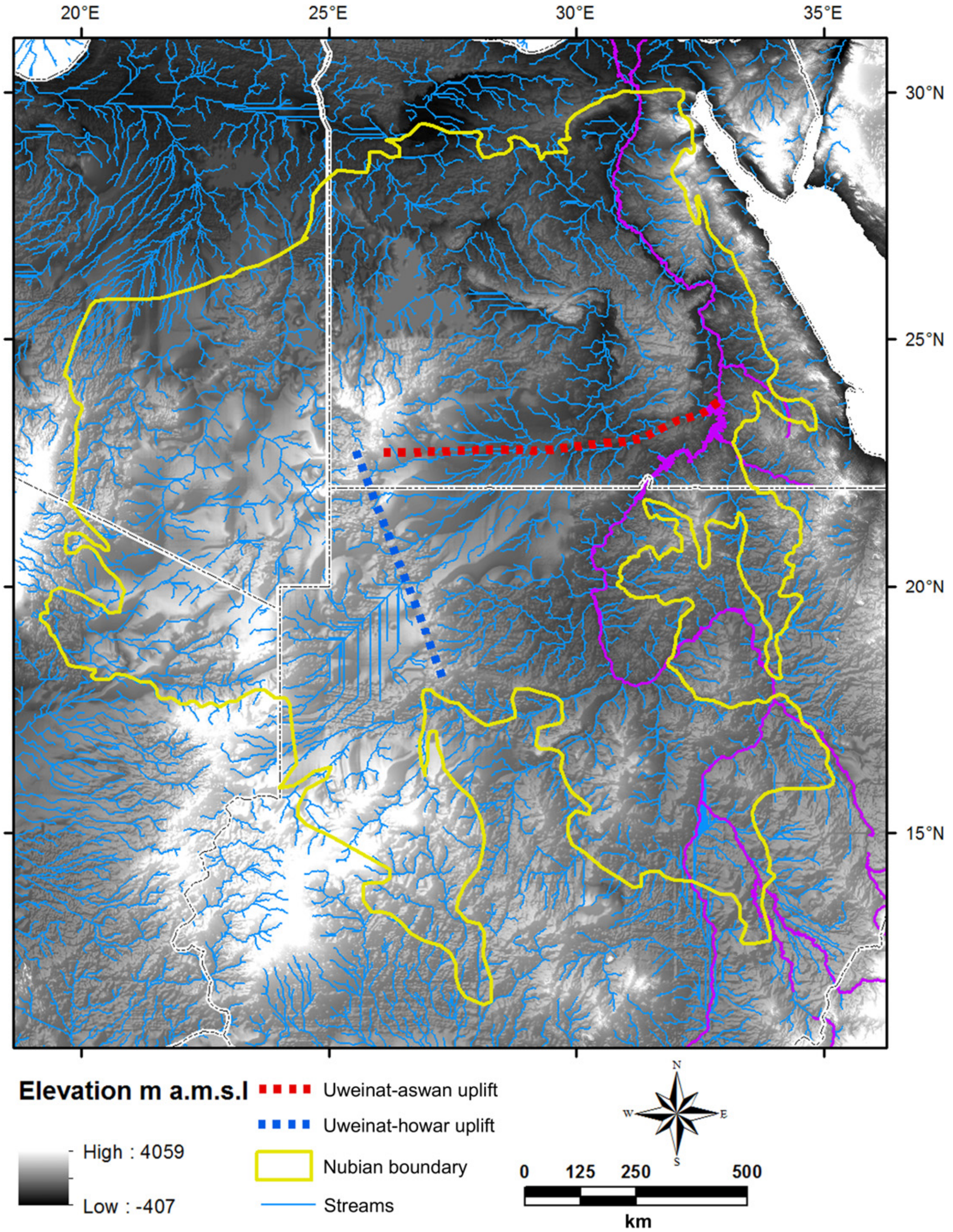
Robinson et al. 2000; Schaber et al. 1997; Stern and Abdelsalam 1996) and to reveal the subtle tectonic fabrics in this area (Abdelsalam et al. 1995; Koopmans and El Fawsti 1996). The buried channels are identified from the differences in SIR-C backscatter between the channels and their surroundings. This difference in backscatter has been attributed to one or more factors (Schaber et al. 1997); (1) concentration of secondary deposits (e.g., iron oxide, calcite, gypsum, halite) with high dielectric permittivity in the channels, (2) abundance of clays that attenuate radar signals, and (3) differences in microroughness between the buried channels and their surroundings.

Using regional SRTM data sets and applying the procedures described above, we mapped the regional extent of drainage networks across the entire areal extent of the Nubian Aquifer and its surroundings (Figure 7). The large sand dune fields in northern Egypt posed a problem for mapping the buried channels, as some dunes are tens of meters high. There, the extracted networks do not reflect the distribution of buried channels, but rather the distribution of elongated lowland fields that separate dunes in these areas. We developed procedures to modify the SRTM data over these areas in ways that strip away the dune fields. Using Landsat Thematic Mapper (TM) images, we first identify all bedrock outcrop locations within the dune fields, then extract the elevation of the individual bedrock locations from SRTM data, and finally generate a modified digital elevation map for the dune field using the generated bedrock elevation data set and applying standard interpolation techniques.

The stream network distribution shown in Figure 7 was generated from SRTM data treated as described above. The displayed stream network distribution covers the following types of channels: (1) active channels that flow year-round (e.g., River Nile Basin channels), (2) ephemeral channels that flow only after a precipitation event (e.g., Eastern Desert and Sinai Peninsula), and (3) buried channels that carried water in previous wet climatic periods but no longer presently flow. Most of the mapped streams are underlain by Nubian Aquifer outcrops, and thus through transmission losses they could have contributed to the recharge of the Nubian Aquifer along their length throughout the previous wet climatic periods.

5.20.7 Patterns of Modern Natural Recharge

We conducted an integrated study (Sultan et al. 2011) using geophysical, geochemical, field and remote sensing data sets, GIS technologies, and continuous rainfall–runoff modeling to examine the validity of a widely accepted notion that the Nubian Aquifer was exclusively recharged by fossil water in previous wet climatic periods in the Quaternary Period. While this statement is largely true for many of the areas occupied by the Nubian Aquifer outcrops, it is not true in areas that receive relatively high modern precipitation. One of these areas is the Sinai Peninsula. In dry climatic periods such as those of today, the precipitation over the mountains in Sinai is channeled downstream over the Nubian outcrops at the foothills of the basement mountainous areas in southern Sinai, providing opportunities for groundwater recharge. In Sinai, we advocated that the Nubian groundwater is a mixture of fossil water and modern precipitation, a model that is supported by interpretations of our geophysical (conventional electrical resistivity) investigations and geochemical data. The interpretation of our geophysical data was found to be consistent with the presence of unconfined Nubian saturated aquifers flooring recharge areas at the foothills of the crystalline basement in the Baraga and Zalaga areas (Figure 8). The isotopic compositions (O, H) for our groundwater samples from wells tapping the Nubian Aquifer underlying recharge areas could be accounted for as mixtures of two endmembers: fossil groundwater with isotopic compositions similar to that of the Western Desert Nubian Aquifer and modern meteoric precipitation, with the latter end member being the dominant component. This


20°E
25°E
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35°E
30°N
25°N
20°N
15°N
Elevation m a.m.s.l
High : 4059
Low : -407
Uweinat-aswan uplift
Uweinat-howar uplift
Nubian boundary
Streams
N
W
E
S
0
125
250
500
km

Figure 7 Distribution of drainage networks across the Nubian Aquifer that was derived from SRTM topographic data. Also shown are the Uweinat-Aswan (dotted red line) and Uweinat-Howar (dotted blue line) uplifts, and outlines of the Nubian Aquifer (yellow line) and river Nile (purple line).

interpretation is supported by the observed increase in modern precipitation from west to east that could explain the progressive west to east enrichment in the isotopic composition of the Nubian Aquifer groundwater. Sinai receives the highest amount of precipitation and its groundwater samples are the most enriched; the Western Desert receives the least amount of precipitation and its samples are the most depleted, while the Eastern Desert receives intermediate amounts of precipitation and the isotopic compositions of its samples are also intermediate.

5.20.7.1 Modeling Modern Recharge of the Nubian Aquifer in Sinai

Conservative estimates for the modern contributions to the Nubian Aquifer in southern Sinai were obtained using

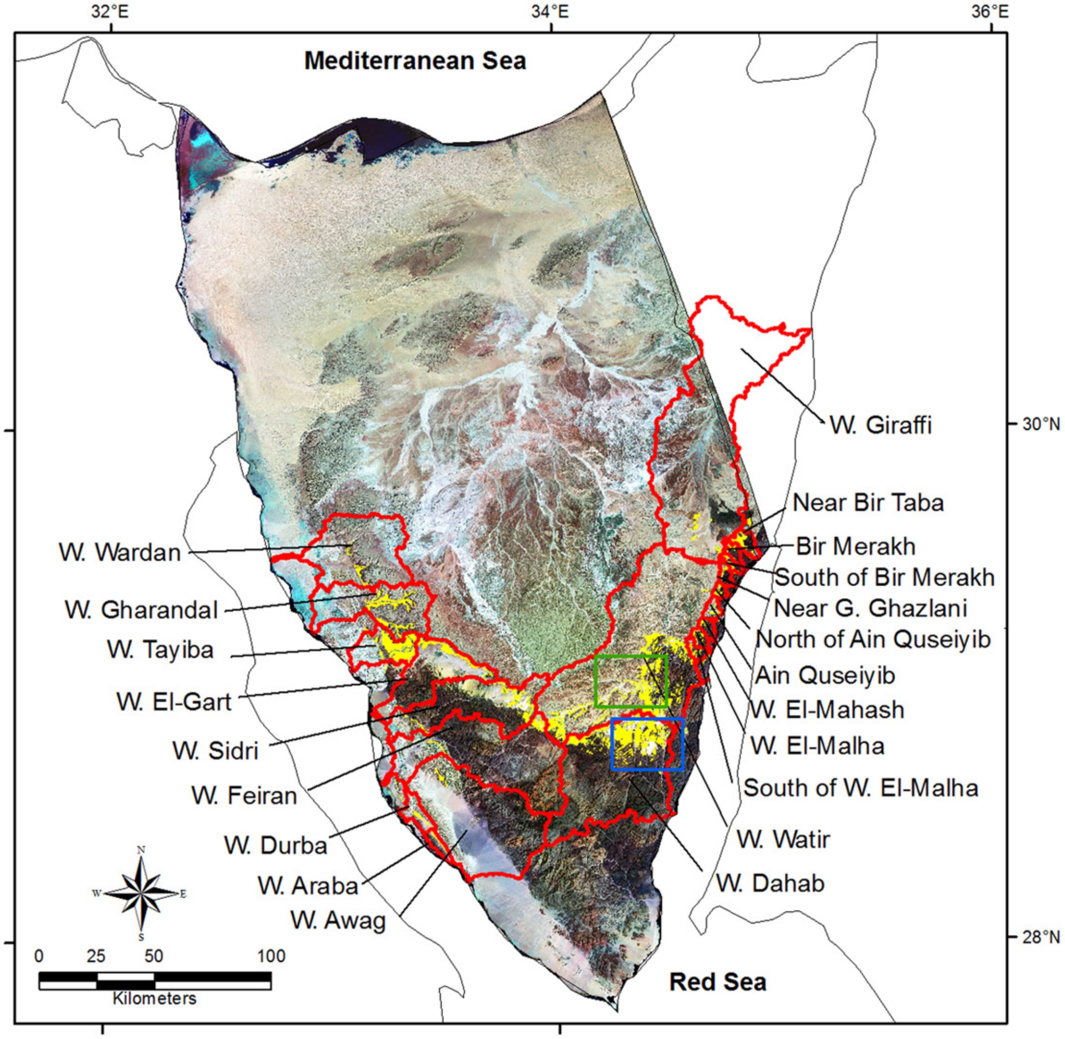
32°E
34°E
36°E
30°N
28°N
Mediterranean Sea
Red Sea
W. Giraffi
Near Bir Taba
Bir Merakh
South of Bir Merakh
Near G. Ghazlani
North of Ain Quseiyib
Ain Quseiyib
W. El-Mahash
W. El-Malha
South of W. El-Malha
W. Watir
W. Dahab
W. Wardan
W. Gharandal
W. Tayiba
W. El-Gart
W. Sidri
W. Feiran
W. Durba
W. Araba
W. Awag
N
W
E
S
0 25 50 100
Kilometers

Figure 8 False color Landsat TM image bands 2-4-7 for southern Sinai showing the 20 watersheds (red outline) encompassing Nubian sandstone outcrops (yellow outline) that were modeled using SWAT continuous rainfall–runoff models. The Baraga and Zalaga areas are outlined by the blue and green boxes, respectively. Modified from Sultan, M., S. Metwally, A. Milewski, et al. 2011: Modern recharge to the Nubian Aquifer, Sinai Peninsula: geochemical, geophysical, and modeling constraints. *J. Hydrol.*, **403**, 14–24.

continuous rainfall–runoff models for the watersheds that crosscut the Nubian Sandstone outcrops and act as potential recharge domains for the Nubian Aquifer.

A hydrologic model for the Sinai Peninsula was constructed within the Soil Water Assessment Tool (SWAT) framework to simulate the hydrologic processes using its physically based formulations. Initial losses and direct overland flows in the Hydrologic Response Units (HRUs) were estimated using the US Department of Agriculture's Soil Conservation Service method (SCS 1972), a method that was successfully applied to similar ephemeral watersheds elsewhere (Gheith and Sultan 2002). The physical properties of the HRUs were largely extracted from databases that we generated throughout our previous studies (Gheith et al. 2001; Gheith and Sultan 2002; Milewski et al. 2009). The soil types were extracted from the 1:500 000 geologic map series (Klitzsch et al. 1987a, 1987b) and the land-use maps were derived from the US Geological Survey 1-km global land use and land cover database (Anderson et al. 1976). Evaporation on bare soils and transpiration on vegetated canopy was calculated using the Penman–Monteith method (Monteith 1981). A simplified top soil profile was used in the model where soil properties were dependent on assigned land use and soil types.

Channel flows were estimated using the Muskingum routing method (McCarthy 1938). Channel flows were subject to transmission losses (Neitsch et al. 2005) and negligible losses to transpiration or evaporation were assumed because vegetation is scarce or absent, flows are short-lived, and alluvial deposits flooring the valleys have high hydraulic conductivities. Simulations were performed at daily time steps, using cumulative 3-hourly TRMM (Tropical Rainfall Measuring Mission) data over periods of 24 h and applying monthly average values for temperature, wind speed, relative humidity, and solar radiation as daily estimates.

The adopted model parameters were extracted from our investigations in the Wadi Girafi watershed (Figure 8; area:

3656 km^2), a watershed that collects precipitation from the highlands of central Sinai (Milewski et al. 2009). Wadi Girafi was selected because, in Sinai, the stream flow data needed for calibration purposes are only available at the outlet (Bottleneck station) of this watershed. Moreover, there are similarities in physical catchment descriptors of Wadi Girafi and those of the other investigated watersheds, and thus the key sensitive model parameters (e.g., SCS curve numbers, groundwater water delays) extracted for the Wadi Girafi could be transferred to similar proximal watersheds. The procedures for calibrating (coefficient of determination, R^2: 0.86; coefficient of efficiency: 0.85) the Wadi Girafi watershed were described in detail in Neitsch et al. 2005.

Continuous rainfall–runoff models were simulated from 1998 to 2007 for 20 watersheds in Sinai (Figure 8) using model parameters extracted from the calibrated Wadi Girafi watershed (Milewski et al. 2009). All of the selected watersheds are located at the foothills of the Precambrian mountains and encompass Nubian Aquifer outcrops. The total area of the modeled watersheds in Sinai is 14 209 km^2, whereas the Nubian outcrops covered approximately 8% of the area of these watersheds. Because watersheds to the north that have Nubian Sandstone outcrops are limited in areal extent, they were excluded; thus, our average annual modern recharge estimates for the Nubian Sandstone aquifer in Sinai should be considered conservative estimates.

5.20.7.2 Findings and Implications

The SWAT model results for each of the investigated 20 Sinai watersheds, including the average annual amount of precipitation, initial losses, surface runoff, total watershed transmission losses, and transmission losses over the Nubian outcrops throughout the investigated period, were summarized in Milewski et al. 2009. Nubian Aquifer recharge was assumed to be equal to the estimated transmission losses, consistent with findings from similar arid environments (Bazuhair and Wood 1996; Dettinger 1989; Flint et al. 2000; Milewski et al. 2009).

First-order estimates for Nubian Sandstone recharge for each of the investigated watersheds were obtained by multiplying the watershed transmission losses by the proportion of Nubian Sandstone outcrops in the watershed. The average annual modern recharge for the Nubian Sandstone in Sinai was estimated at $13.0 \times 10^6\,\mathrm{m}^3$ from the sum of annual transmission losses for 20 watersheds for each of the investigated years (1998–2007) averaged by the number of years (10 years).

These findings highlight the importance of modern local recharge of the Nubian Aquifer and bear on its sustainable exploitation in the Sinai and elsewhere where the aquifer is being locally recharged. There are many similar areas that are being recharged by modern precipitation across the Nubian Aquifer. Figure 9 shows estimates of cumulative (2002–09) precipitation over the Nubian Aquifer derived from TRMM 3B42v6 data. Inspection of Figures 1 and 9 shows extensive Nubian Sandstone outcrops south of latitude 29°, and large sectors of these areas, south of latitude 17°, receive substantial precipitation (up 1200 mm yr^{-1}). It is in these areas that the Nubian Aquifer is receiving modern recharge.

5.20.8 Modern Recharge Due to Manmade Structures

Modern recharge of the Nubian Aquifer is not restricted to natural recharge in high-precipitation areas. Building dams can enhance local recharge of the Nubian Aquifer from the large water bodies impounded behind dams. Egypt has increased its water storage capacity by constructing the Aswan Dam and the Aswan High Dam. The construction of the latter entailed the development of an extensive reservoir, Lake Nasser, designed to have a maximum water level 183 m above sea level, a total capacity of $1.6 \times 10^{11}\,\mathrm{m}^3$, a total length of 500 km, and an average width of 12 km (Figure 10) (Said 1993). The project raised the surface water behind the High Dam and resulted in recharge of the aquifer, which previously was discharging into the Nile. Because the Lake Nasser reservoir has approached its maximum storage capacity in the past few years, the depressions to the west in the southern Western Desert of Egypt (Figure 10) are currently being used as a natural flood diversion basin to reduce possible downstream damage to the Nile Valley caused by exceptional flooding. These additional artificial lakes are also recharging the aquifer.

5.20.8.1 Modeling the Impacts of the Aswan High Dam on the Nubian Aquifer

We constructed two-dimensional groundwater flow models to investigate the long-term hydrologic impacts of Lake Nasser in southwest Egypt (Kim and Sultan 2002; Yan et al. 2003). To fully capture interactions between the surface and groundwater in the study area, the model domain included the area covered by the entire Lake Nasser in Egypt and Sudan, the Tushka lakes, and their surroundings. The stages and the temporal variations (over the period 1967–2002) in the areal extent of the lakes under investigation were extracted from CORONA satellite images, Landsat TM, and Digital Terrain Elevation Data (DTED) data and from recorded (1967–2000) surface-water levels for Lake Nasser. The Corona satellites were used for photographic surveillance of strategic areas beginning in June 1959 and ending in May 1972. The topography of the area now covered by water in Lake Nasser was estimated from: (1) the areal extent of Lake Nasser in 1967 (CORONA) and 1972 Multi Spectral Scanner, (2) DTED acquired in 1989, and (3) historic lake levels. Our approach involves the development of a groundwater flow model through identification of model boundaries and initial conditions, then calibration of the model over a 30-yr period (1970–2002). Because the study area is mostly unconfined with relatively simple geologic settings (especially near the lake), a two-dimensional unconfined groundwater flow model was found to be adequate for our modeling purposes. A modular three-dimensional finite-difference groundwater flow model (MODFLOW) (McDonald and Harbaugh 1988) was used to develop the model for the Nubian Aquifer in the study area.

Because the basement crops out to the east and southeast, the model boundaries along these domains were considered as no-flow boundaries. Constant head and variable head equal to the Nubian water table level were prescribed along the southwestern and northern boundaries, respectively (Figure 10(a)). The rationale for this type of boundary condition is the almost constant groundwater level over the past two decades along the

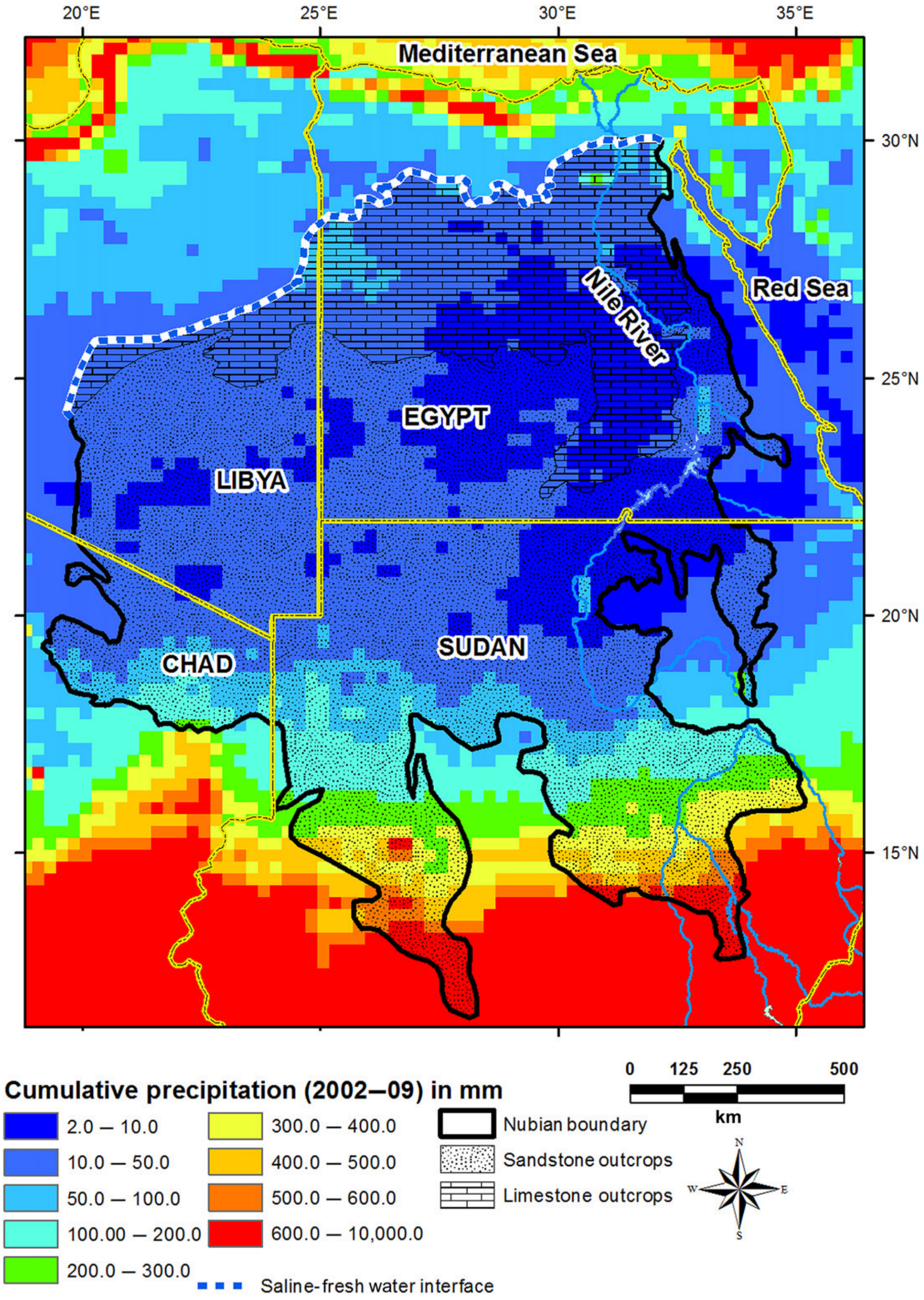
20°E
25°E
30°E
35°E
30°N
25°N
20°N
15°N
Mediterranean Sea
Red Sea
Nile River
EGYPT
LIBYA
SUDAN
CHAD
0 125 250 500
km
Cumulative precipitation (2002–09) in mm
2.0 – 10.0
10.0 – 50.0
50.0 – 100.0
100.00 – 200.0
200.0 – 300.0
300.0 – 400.0
400.0 – 500.0
500.0 – 600.0
600.0 – 10,000.0
Nubian boundary
Sandstone outcrops
Limestone outcrops
Saline-fresh water interface
N
E
S
W

Figure 9 Extent of the Nubian Aquifer, surface geology, and 8-year cumulative precipitation. Source: Derived from TRMM data.

southwestern and northern boundaries. The study region was discretized using orthogonal grids of rows (590) and columns (608) varying in length between 0.5 and 5.0 km with finer grids located at and near the lake. Null properties were assigned to cells outside the model domain. The development and calibration of the model were conducted with the Groundwater Modeling System developed by the US Department of Defense (DoD 1998). The modeling area covers almost all of the existing pumping and monitoring wells, the Tushka Canal, and all of the proposed new irrigation localities.

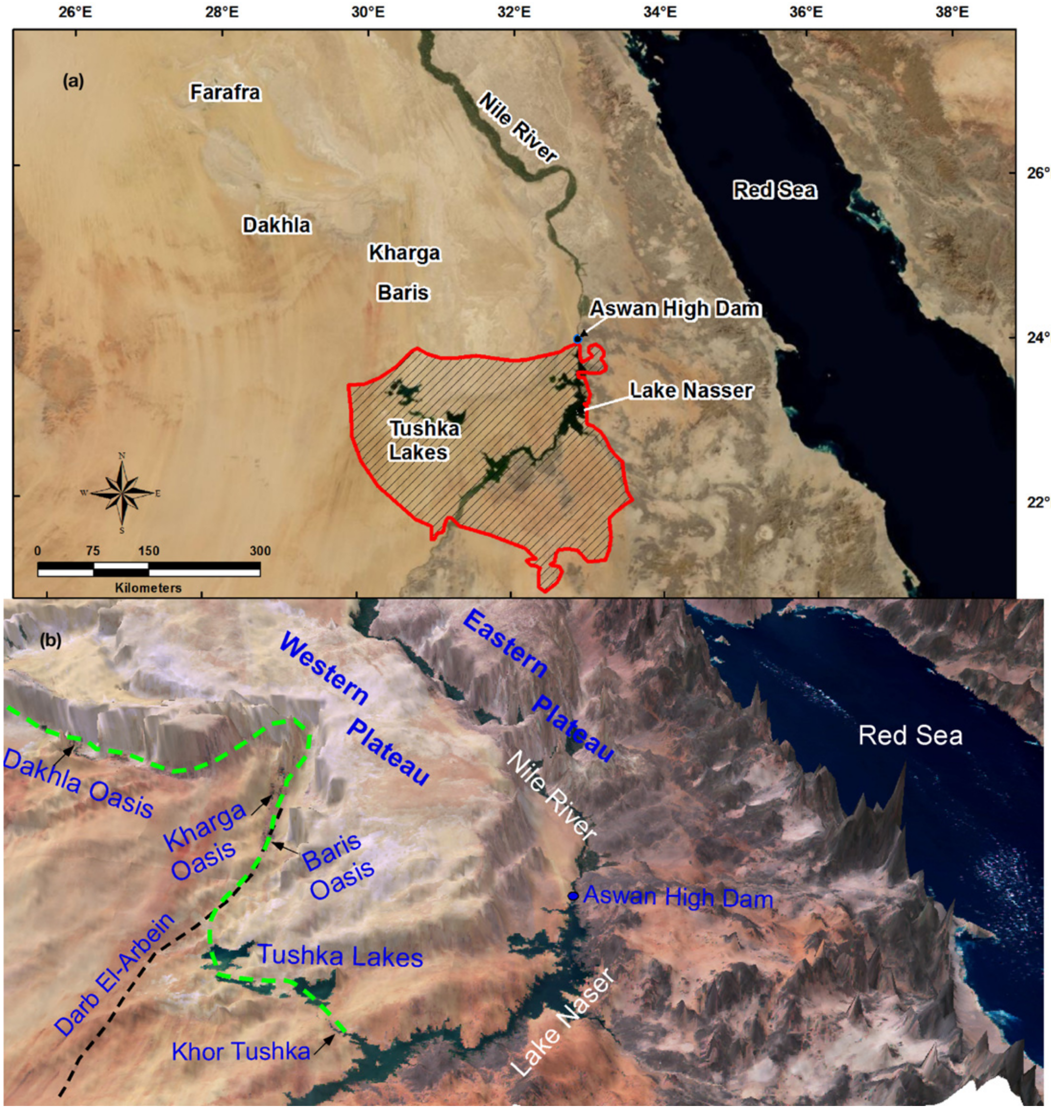
26°E
28°E
30°E
32°E
34°E
36°E
38°E
26°N
24°N
22°N
(a)
Farafra
Nile River
Red Sea
Dakhla
Kharga
Baris
Aswan High Dam
Lake Nasser
Tushka Lakes
N
S
E
W
0
75
150
300
Kilometers
(b)
Western Plateau
Eastern Plateau
Red Sea
Nile River
Dakhla Oasis
Kharga Oasis
Baris Oasis
Aswan High Dam
Tushka Lakes
Darb El-Arbein
Khor Tushka
Lake Naser

Figure 10 MODIS image acquired over Egypt on 19 February 2000, showing Lake Nasser, the eastern and western plateaus bounding the River Nile valley, the Dakhla, Kharga, and Baris oases, Tushka spillway, and Tushka lakes west of Lake Nasser that formed in the depressions within the western plateau after lake levels peaked in 1997. (a) Model domain (hashed area) and boundary (red line). (b) Three-dimensional representation of MODIS draped on topography showing proposed scenario (dashed green line) to channel excess Lake Nasser water across the western plateau in high flood years.

Transient flow simulations were required for model calibration over the calibration period from 1970 to 2002. The calibration was carried out by a trial-and-error fit of simulated groundwater heads to measured values. Calibration targets were established for the residual error statistics, and groundwater parameters were modified until the targets were satisfied. Data availability in the study area was generally limited. More wells are currently being drilled as the Tushka Canal project progresses. Luckily, the older wells (drilled from 1965 to 1980), though limited in number, are concentrated along the lake shoreline, where the interaction between the lake and the aquifer is most pronounced, enabling calibration of the model with confidence. Hydraulic conductivity values and yield coefficients of the aquifer materials and vertical hydraulic conductivity of the clay layer were the principal parameters varied during calibration. Because of the rare precipitation (EMA 1996) and negligible pumping activities, largely restricted to pumping tests (Abdel Karim 1992), precipitation and pumping were assumed negligible throughout the calibration. Anisotropy was also assumed to be negligible. Figure 11 shows a comparison between computed and observed head data at the initial reservoir storage stage (1970), peak lake-level years (1980 and 2000), and low lake-level year (1989). The simulated heads from the calibrated model have a good agreement with observed heads throughout the calibration period.

5.20.8.2 Findings and Implications

Transient simulations suggest that the Nubian Aquifer is significantly affected by recharge from Lake Nasser. The total recharge from Lake Nasser to the aquifer for the period

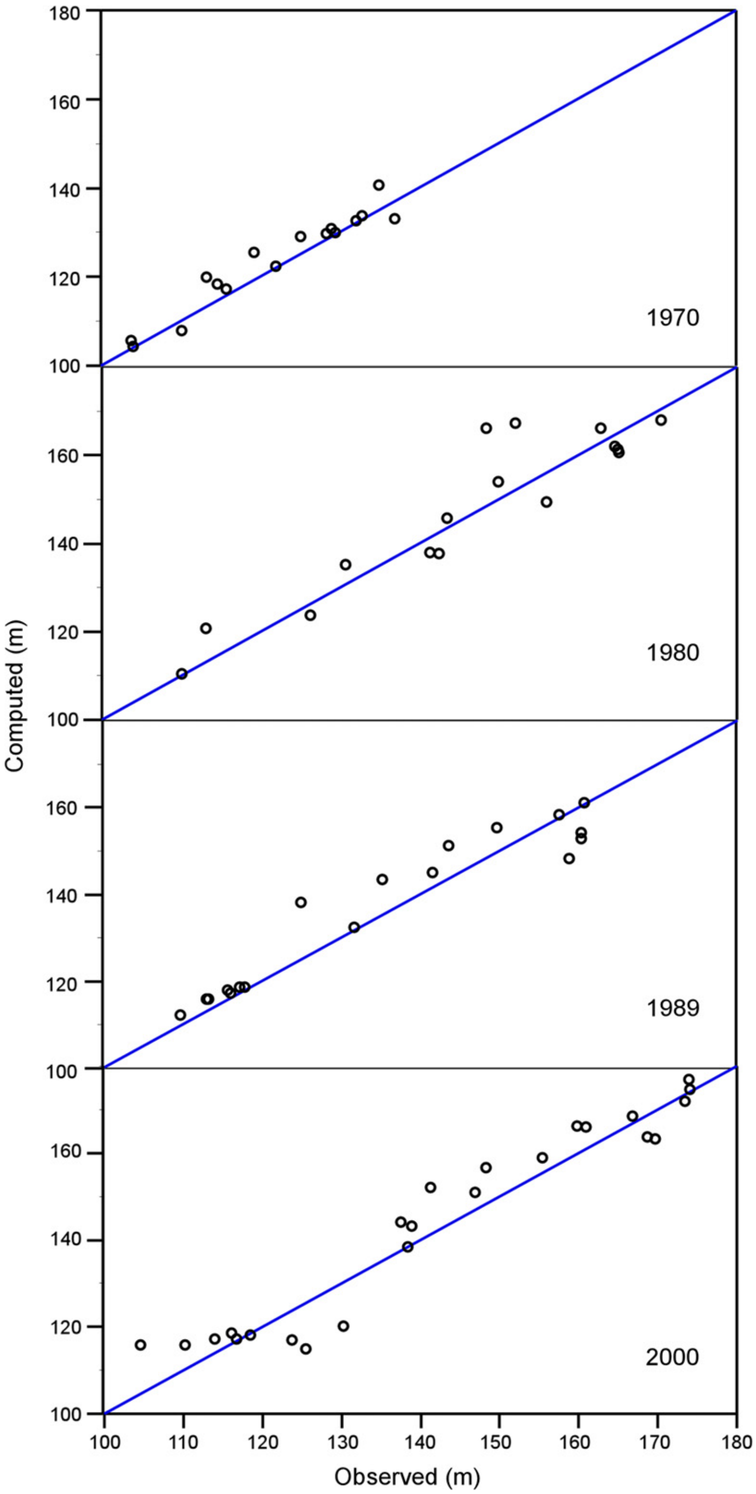

Figure 11 Comparison between computed and observed head data for the years 1970, 1980, 1989, and 2000.

1970–2002 amounts to 10^{11} m^3, which is about 60% of total lake capacity. The peak recharge occurred in the periods between 1975 and 1983, amounting to 6 × 10^{10} m^3, and between 1993 and 2001, amounting to 4 × 10^{10} m^3 (Figure 12). These two periods (1975–83 and 1993–2001) correspond to high lake levels (Figure 12) caused by high inflow to River Nile from the south. Between these two periods, from 1984 to 1987, lake levels dropped below the groundwater table; this resulted in the discharge of groundwater from the aquifer back to the lake. The dynamic change in recharge to the aquifer, as simulated by the calibrated model, indicates a rapidly increasing recharge during the initial

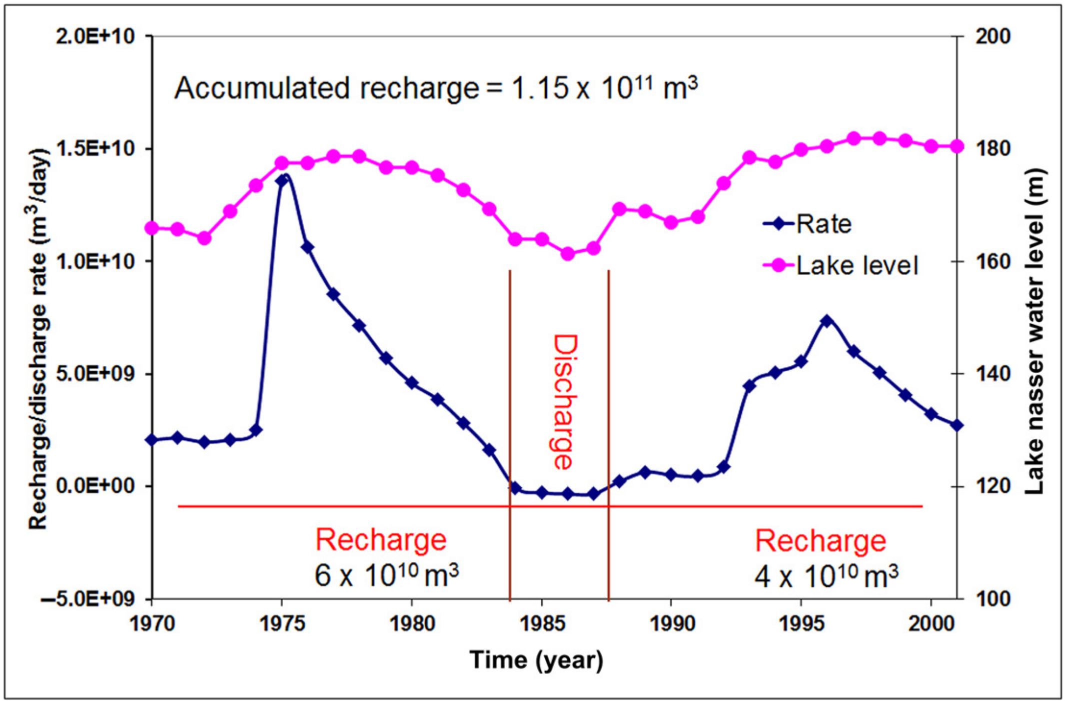

Figure 12 Model outputs: recharge from Lake Nasser to the Nubian Aquifer throughout the calibration period (1970–2002); surface-water levels for Lake Nasser are also shown.

reservoir building period and a gradually decreasing recharge after the lake level and recharge rate peaked. The trend of decreasing recharge is consistent with the gradual reduction of hydraulic gradient between the lake stage and the groundwater level in the Nubian Aquifer. For example, after the lake reached maximum storage capacity, annual recharge decreased by 15–20% each year, from $7.4 \times 10^9\,\mathrm{m}^3\,\mathrm{yr}^{-1}$ in 1996 to $2.7 \times 10^9\,\mathrm{m}^3\,\mathrm{yr}^{-1}$ in 2001.

This progressive decrease in recharge translated into excess water that has been encroaching onto the surrounding depressions. Since 1998, excess water in Lake Nasser has been routed through existing flood diversions to the Tushka lakes and through release of water into the Nile course. The development of the Tushka lakes, changes in lake extent, and lake stages were analyzed using a series of Landsat TM, Moderate Resolution Imaging Spectroradiometer (MODIS), Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER), and shuttle images, as well as DTED and ASTER-derived elevation data. The first lake, which emerged in late 1998 on the Tushka depression west of Lake Nasser, covered an area of 400 km^2, with a lake stage 172 m above mean sea level (AMSL). In 2000, excess water from Lake Nasser spread farther west, forming three additional lakes across a lowland area of 750 km^2, with lake stages decreasing from east to west (162 m AMSL at the second lake to 147 m AMSL at the fourth lake). In 2002, the fifth lake developed to the northwest with a lake stage of 144 m AMSL. The five newly developed Tushka lakes cover a total area of 1300 km^2, which is more than 20% of the area of Lake Nasser at maximum capacity (Figure 13).

We developed a surface-water model and calibrated the model by adjusting routing parameters against lake stages identified for 1998–2002. The recharge to the Nubian Aquifer is negligible because most of the Tushka lakes are floored by largely impermeable massive limestone and underlying shales. Simulations indicate that the total volume of water naturally diverted from Lake Nasser to the five Tushka lakes from late 1998 to early 2002 is about $2.74 \times 10^{10}\,\mathrm{m}^3$. Of the diverted water, 61% is stored in the five Tushka lakes and 39% is lost to direct evaporation. If the lake level remains at a maximum, the simulated prediction based on the calibrated model suggests that lakes will continue to develop to the northwest, toward the lowlands west of the plateau, where the permeable Nubian sandstone crops out. Further development of new lakes could potentially generate significant recharge of fresh water to fossil groundwater in the underlying Nubian Aquifer and provide opportunities for sustainable agriculture for the first time in these areas.

5.20.9 Location and Magnitude of Modern Discharge

Many of the areas of natural discharge within the Nubian Aquifer have gone undetected. The discharge has been long recognized as flowing springs within depressions (e.g., Kharga, Dakhla) and along the coastal plain of Gulf of Suez (Sturchio et al. 1996). Using isotopic and geochemical analyses along with field and remote sensing data, we have shown (Sultan et al. 2007) that discharge of the Nubian Aquifer in Wadi Asyuti, an area proximal to the River Nile valley (Figure 1), and in Egypt at large is occurring along the fault complex that defines the River Nile and the Gulf of Suez, where ascending groundwater accesses deep-seated fault systems and discharges into relatively thick alluvial aquifers proximal to these two fault complexes.

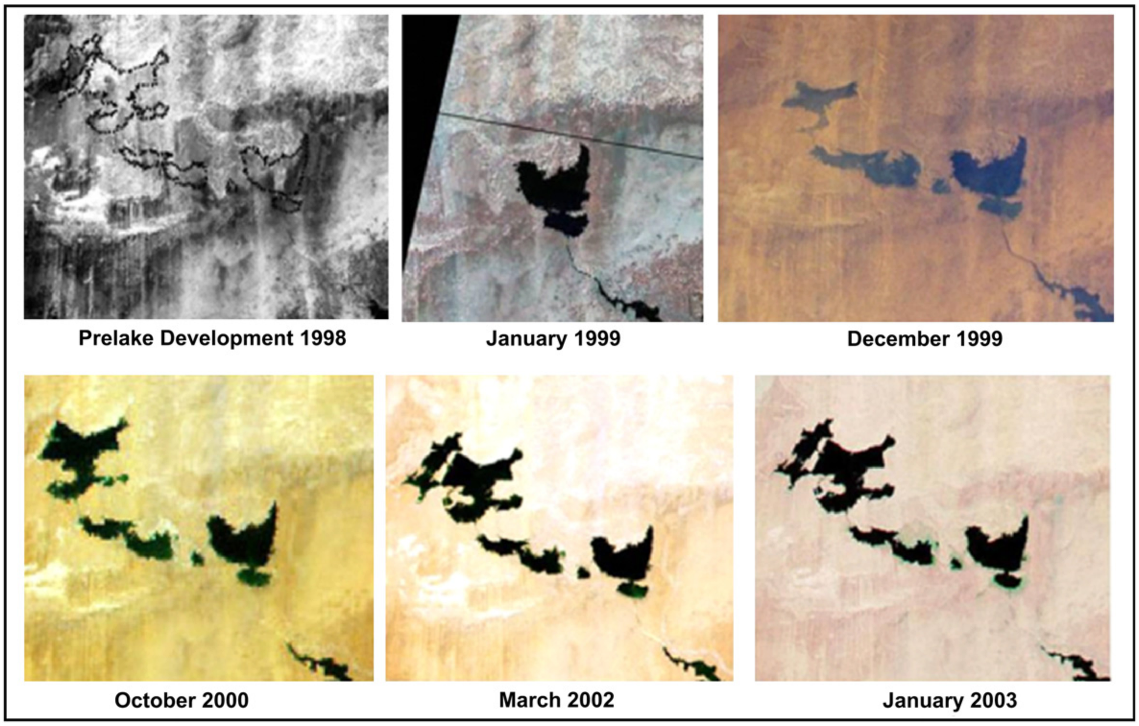

Figure 13 Temporal (1998–2003) satellite data showing the development of the Tushka lakes.

In Wadi Asyuti, all of the collected groundwater samples (eight samples) showed depleted isotopic compositions (δD: $-34.68‰$ to $-51.96‰$). These depleted compositions, undetectable tritium (<1 TU), and discharge temperatures (27–32 °C) indicatethat these waters are paleowaters, largely derived from the underlying Nubian sandstone. In this area, the Nubian sandstone is found at depths exceeding 1 km; thus, the groundwater must have ascended via deep-seated faults. Three major subvertical, northwest-trending faults were identified along cross section B-B′ (inset Figure 14) using geophysical data and utilizing information extracted from drilling (RIGW 1993). The thickness of the alluvium aquifer significantly increases (to more than 300 m) from the northeast to the southwest. The location of these subvertical faults plots along northwest-trending structural discontinuities that could be readily identified on Landsat TM images and on digital topography. Figure 14 is an overlay of Landsat TM data over digital elevation, an image that integrates and displays information contained in the two datasets. Inspection of the image shows that topographic expressions (valleys and grabens) mark the projected extensions of the traces of three northwest-trending faults into the adjacent mountains. A two-dimensional groundwater flow model was constructed and calibrated against head data from 19 wells to assess the discharge and to demonstrate a replicable model for similar reservoirs. Results point to a significant contribution to the Asyuti groundwater system from rising Nubian groundwater ($3.19 \times 10^7\,\mathrm{m^3\,yr^{-1}}$: 75% of incoming flow) and point to similar settings for large-scale natural discharge along the length of the River Nile in Egypt and Sudan and along the Gulf of Suez.

5.20.10 Scenarios for Recharging the Nubian Aquifer

It is suggested here that Egypt could develop sustainable agriculture practices in the Western Desert by channeling the encroaching Lake Nasser waters in high flood years across the western plateau reaching the lowlands west of the plateau that are largely underlain by Nubian Sandstone. This could be accomplished by deepening the canals joining the natural depressions and extending the deepened canal system across the western margin of the plateau. In high flood years, the channeled excess Lake Nasser waters will flow down gradient along Darb El Arbeen toward the Baris, Kharga, and Dakhla oases (Fig. 10b), where the water could be used for sustaining and expanding the agricultural communities and for recharging the fossil waters of the Nubian Aquifer in these areas. This solution will minimize water loss to direct evaporation (39% excess water) and address the steady decline (up to $2\,\mathrm{m\,yr^{-1}}$) in groundwater levels in the oases that have been recorded for the past 60 years. Excess Lake Nasser waters could be channeled via canals, piped, or even allowed to flood Darb El Arbeen (Fig. 10b). Prior to the construction of the Aswan dam, Nile waters flooded the Nile banks, depositing soils and bringing nutrients to the flooded areas; following the recession of the waters, the Egyptian peasants cultivated these rich soils. Similar, but not necessarily identical, scenarios could be adopted in the Western Desert. However, careful consideration must be given to protection or relocation of existing infrastructures in these areas, and to the prevention of aquifer contamination by agricultural and industrial chemicals in the surface waters.

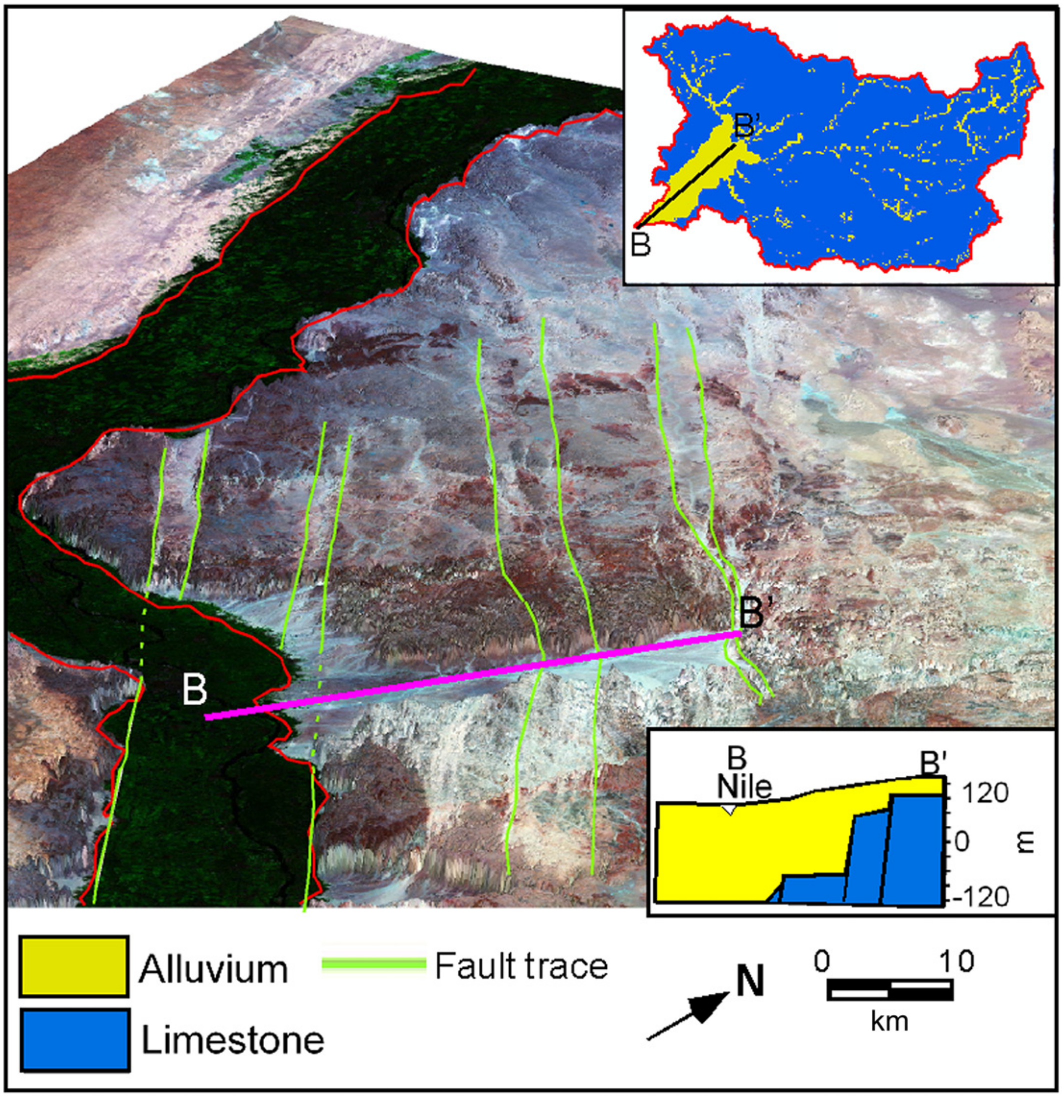

Figure 14 Landsat TM image (false color image) for the Wadi Asyuti area and surroundings draped on digital elevation data. Upper right inset: Asyuti watershed with network of channels flowing from the Red Sea hills toward the Nile River valley; main rock units are Quaternary alluvial deposits (yellow) and Tertiary limestone (blue). Lower right inset: cross section along traverse B–B′ (simplified from Rossignol-Strick, 1983). Topographic expressions (valleys and grabens) mark the projected extensions of the traces of northwest-trending faults identified by drilling and by geophysical methods into the adjacent mountains. (For interpretation of the references to color in this figure legend, the reader is referred to the web version of this book.) Source: Modified from Sultan, M., E., Yan, N., Sturchio, et al. 2007. Natural discharge: a key to sustainable utilization of fossil groundwater. *J. Hydrol.*, **335** (1–2), 25–36.

5.20.11 Development of Realistic Groundwater Flow and Age-Mass Transport Models for the Nubian Aquifer

The majority of the Nubian Aquifer models apply a simple piston flow system with one recharge source and are calibrated against current hydraulic heads (e.g., Brinkmann et al. 1987; Euroconsult-Pacer 1983; Soliman et al. 1998). Development of more realistic models for the Nubian Aquifer System could assist in understanding complex flow systems and in predicting hydrologic responses to anthropogenic controls and projected climatic changes. The model could also be used to assess the impacts of various water resource management schemes. The advocated model might incorporate a regional flow system initiated by continuous recharge from mountainous areas in Chad and along the Red Sea hills, localized historical recharge from surface-water infiltration during wet climatic periods (refer to Sections 5.20.1 to 5.20.3), and discharge through a chain of oases in the Western desert and along the deep fault systems that bound the Nile Valley and the Gulf of Suez (Yan et al. 2004; Sultan et al. 2007). Transient flow models should be constructed to run for hundreds of thousands of years given the known ages of the groundwater (up to 1 million years) (Sturchio et al. 2004). Because flow simulations for hundreds of thousands of years that are calibrated against current hydraulic heads are probably unreliable at best, a model that is capable of simulating the groundwater age distribution and the ages of the paleochannels would be more representative of the system.

The construction and calibration of the advocated model may require (1) development of a conceptual model that integrates geological, hydrogeologic, geochemical, and remote-sensing data listed in this study and from all available other sources for the Nubian Aquifer System; (2) construction of a transient numerical flow model that accounts for the continuous recharge from the south (Chad) and from the Red Sea hills, for the local intermittent recharge during wet periods, and for the discharge in the oases and along the River Nile; and (3) collection of a comprehensive groundwater age data set across the Nubian Aquifer and simulation of observed groundwater age distribution using the Goode's age-mass advection–dispersion–diffusion transport equation.

The developed conceptual models for the Nubian groundwater system should account for the distribution of delineated subbasins, paleo-recharge areas, paleodrainage patterns, paleochannel sedimentary systems, discharge areas, and groundwater ages in conjunction with geological stratigraphic and hydrological data. The conceptual model should address lateral and vertical discontinuities that significantly affect the flow system. A large-scale three-dimensional numerical flow model could be constructed to cover the entire Nubian Aquifer. The model should account for the observed vertical and lateral variations in the lithologic sequences of the Nubian Aquifer System (four major water-bearing horizons: A through D) and their corresponding hydraulic parameters. The hydrogeological parameters (e.g., hydraulic conductivity, storage coefficients, aquifer thickness) can be extracted from many published data (Euroconsult-Pacer 1983; Hesse et al. 1987; WPRP 1998).

The time period for the transient flow model should be constrained by the existing constraints on the timing of pluvial periods for the last 400 000 years (Crombie et al. 1997; Crombie et al. 1999; Rossignol-Strick 1983; Sultan et al. 1997; Szabo et al. 1995). Several intermittent periods of wetter conditions occurred during the last 400 ka, with the most recent recharge occurring between 9.5 and 4.5 kyr B.P. Arid conditions may have prevailed between about 10 and 20 ka (Brinkmann et al. 1987; Pachur and Roper 1984). Under semiarid conditions between 25 and 40 ka, groundwater recharge from an estimated 200–250 mm rainfall is <30 mm yr^{-1} (Hesse et al. 1987; Pachur and Kropelin 1987). These precipitation rates were inferred from the distribution of prehistoric floral and faunal remains (Hassan 1996; Kowalski et al. 1989). For modeling purposes, our findings, these published data sets, and other published data sets could be used to define (1) timing of historic stresses for the transient flow model(s), corresponding to the known periods of wet and dry climate conditions, and (2) precipitation and recharge during these periods. Areas of continuous recharge should be limited to the southernmost mountainous area (in Chad) and along the Red Sea hills. The current recharge rates in these areas should be estimated using the continuous simulator. Local area(s) that witnessed intermittent recharge during previous wet climatic periods in southern Egypt and northwestern Sudan can be defined from the distribution of Nubian Sandstone outcrops and the inferred paleochannel sedimentary system. Discharge in the oases of the Western Desert and along the Nile and the Gulf of Suez fault complexes is also an important model element.

An age-mass transport model (Goode 1996) can be constructed to simulate the observed groundwater age distribution. The age-mass is the product of water mass and its age. The initial age-mass for the entire aquifer system is highly uncertain. However, for a 400 000-year simulation, the groundwater age in most of the investigated area is probably insensitive to the initial age. The simulated groundwater should be calibrated against the ages of groundwater samples. The calibration can be accomplished via an iterative process of adjusting specific flow and mass transport parameters, such as hydraulic conductivity, recharge rate, recharge duration, conductance for drains in oases and seepages along the Nile Valley, evaporation rate, longitudinal and vertical dispersivities, and diffusion coefficients to achieve the best agreement. The advocated model will provide an effective tool to investigate the responses of the aquifer system to climate, water extraction scenarios, anthropogenic factors, and various water resource management strategies.

5.20.12 Findings

If we were to generalize our findings in Egypt and in northern Sudan (Selima sheet catchment) to the remaining parts of the Nubian Aquifer and take into consideration the existing meteorological data, GRACE gravity data, and isotopic and geochronologic data for groundwater, remote sensing and geophysical data, and our simulations from hydrologic models, the following picture would emerge: (1) the Nubian Aquifer System is more likely to be formed of a number of discrete subbasins that are largely disconnected from one another, and within each of these postulated subbasins the ages of the groundwater will increase along the flow direction; (2) during wet climatic periods, precipitation was widespread across the entire Nubian Aquifer and autochthonous recharge was occurring within each of the subbasins in areas where the Nubian sandstone crops out; (3) autochthonous paleo-recharge was probably occurring through transmission losses from paleodrainage systems, currently buried under the sand sheets; (4) precipitation has been continuous over Chad and surrounding areas and probably intensified during the wet climatic periods; (5) the Nubian Aquifer is receiving modern recharge on a regional scale in the south (Chad and Sudan) and locally in areas in the north (e.g., Sinai) where the exposed aquifer rocks receive relatively large amounts of precipitation that are channeled by streams or are precipitated directly over the Nubian outcrops; (6) the construction of the Aswan High Dam raised the surface-water levels in Lake Nasser behind the dam, reversed groundwater flow direction, and recharged the aquifer with $10^{11}\,\mathrm{m}^3$ of Lake Nasser's water throughout the period 1975–2001; (7) many of the areas of natural discharge within the Nubian Aquifer have gone undetected, and discharge of the Nubian Aquifer is largely occurring along the fault complex that defines the River Nile and the Gulf of Suez where ascending groundwater accesses deep-seated fault systems and discharges into relatively thick alluvial aquifers proximal to these two fault complexes; and (8) analysis of interannual mass variations from monthly GRACE solutions that span the period from April 2002 through November 2010 indicated near-steady-state solutions in the south (Sudan: $0.69 \times 10^9\,\mathrm{m}^3\,\mathrm{yr}^{-1}$, $0.8\ \mathrm{mm\ yr}^{-1}$; Chad: $-0.12 \times 10^9\,\mathrm{m}^3\ \mathrm{yr}^{-1}$, $-0.9\,\mathrm{mm\,yr}^{-1}$) and in Libya ($-0.39 \times 10^9\,\mathrm{m}^3\ \mathrm{yr}^{-1}$, $-1.1\,\mathrm{mm\,yr}^{-1}$), and declining water supplies in the north (Egypt: $-2.35 \times 10^9\,\mathrm{m}^3\,\mathrm{yr}^{-1}$, $-3.5\,\mathrm{mm\,yr}^{-1}$) that are apparently largely related to progressive increase in extraction rates with time.

Future work should concentrate on research activities to enable the following: (1) further examination and refinement of our preliminary model/concept in Egypt, (2) examining the relevance of the developed models/concepts to other parts of the Nubian Aquifer System, and (3) developing realistic numerical models for the Nubian Aquifer System that are constrained by published and newly acquired data.

We provided two test cases to address sustainable management of the Nubian water. The first estimates the average annual recharge for the Nubian Aquifer in Sinai in an attempt to identify sustainable extraction in this area. Sustainable use of the Nubian Aquifer water in areas of relatively high precipitation could be attained if extraction from the aquifer did not exceed the average amounts of modern recharge for the same time period. The amount of recharge could be enhanced by the construction of dams in areas of relatively high precipitation to enhance recharge and to decrease losses to runoff. The second approach is suggested to supplement the fossil groundwater extracted from the aquifer and is proposed for areas where temporal mass variations indicate progressive depletion of the aquifer with time due to excessive extraction. The approach calls on channeling excess Lake Nasser water in years of high flood to the Western Desert to replenish the progressively depleted Nubian Aquifer in this area. Long-term strategies for sustainable management of the Nubian Aquifer will require the construction of improved hydrologic models that can account for the geological, hydrogeologic, geochemical, geochronologic, geophysical, and remote-sensing observations and findings discussed here and that can simulate the observed groundwater age distribution. These models should have the necessary resolution for predicting the near-term effects of extraction, artificial recharge, and potential for aquifer contamination by recharging water, as well as the longer-term effects of climate.

5.20.13 Implications for the Vulnerability of the Nubian Aquifer

Studies, such as those presented and proposed here, are required if we are to address the projected vulnerabilities of the Nubian Aquifer over the next few decades. The Nubian Aquifer is vulnerable from a number of perspectives. The increasing population in the region, as well as effects of climate and its resultant impacts on sea level and the water cycle dynamics, is predicted to create substantial demand for increased production of groundwater from the Nubian Aquifer System. We have shown that even at current rates of extraction, the Nubian Aquifer is being gradually depleted by extraction and natural discharge.

The population in Egypt is expected to approach 100 million by the year 2025 with the fresh water supply decreasing to 337 m^3 per capita (AbuZeid and Hefny 1992). Considering that about 80% of Egypt's water use is already consumed by agriculture, the production of sufficient food for the population will necessitate improvements in agricultural water use efficiency and may require the development of new agricultural lands that need to be irrigated with groundwater. Furthermore, as upstream population in the Nile Basin continues to grow, there could be increased demand on the Nile River before it reaches Egypt. The 1959 treaty that guarantees Egypt an annual Nile water allotment of $55.5 \times 10^9\ \mathrm{m}^3$ is now being challenged by River Nile Basin countries in the upstream. The gradual increase in global temperatures will increase evaporative losses from the surface of the river and Lake Nasser. Furthermore, many global climate model scenarios for the Nile Basin region predict a net decrease in Nile flow (Strzepek et al. 2001).

A gradual rise in sea level is predicted as a consequence of global warming. In Egypt, most of the agricultural production occurs in low-lying lands of the Nile Delta, and inundation of delta farmlands will create an urgent need for additional agricultural land development and irrigation to ensure food supply to the population. As much as 26% of the habitable land in the Nile Delta could be lost to sea level rise and delta subsidence by the year 2100 (Milliman et al. 1989). This massive land loss will cause large-scale migration to presently undeveloped land, and much of this development will have to occur outside the Nile Valley in regions dependent on groundwater for irrigation. The increasing population, along with increasing land use for agricultural and industrial production, will contribute to an increase in polluted wastewaters. Improper wastewater treatment practices could result in contamination of groundwater aquifers.

Mitigation of the effects of population increase, climate, and sea level rise can be achieved in part by increasing water use efficiency and promoting water conservation and recycling. However, it is inevitable that the demand for fresh water will outpace the supply, and new sources of fresh water will be imperative. The extraction of Nubian Aquifer groundwater is certainly destined to substantially increase as demand grows. Increasing amounts of groundwater extraction may eventually aggravate transboundary water disputes (Maxwell 2011). Armed conflict has already occurred for decades in the Aouzou Strip along the Chad-Libya border, in part related to Nubian water usage. The respect of sovereign rights to water resources within national boundaries is often at odds with the concept of shared transboundary resources such as the Nile River and the Nubian Aquifer.

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5.21 Climate Vulnerability on the Water Resources Systems and Potential Adaptation Approaches in East Africa: The Case of Ethiopia

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5.21.1 Introduction

Many areas in Africa are already recognized as water stressed and highly vulnerable to climate impacts mainly because of having climates that are among the most variable in the world on seasonal and decadal time scales. Estimates indicate that one-third of the African people are already living in drought-prone areas and 220 million are exposed to drought each year (UNFCCC 2007). It has been already recognized that many factors contribute to compounding the vulnerability and will have negative effects on the continent's ability to cope with climate and other threats (UNDP 2006). Examples of such factors are poverty, illiteracy and lack of skills, weak institutions, limited infrastructure, lack of technology and information, low levels of primary education and health care, poor access to resources, low management capabilities, and armed conflicts. These factors contribute to low adaptive capacity and societal resilience to changes and an overexploitation of land resources in Africa. UNFCCC (2007) reports that Africa will face increasing water scarcity and stress with a subsequent potential increase of water conflicts, as almost all of the 50 river basins in Africa are transboundary.

The situation in eastern Africa, and particularly Ethiopia, is no different from the continental situation. There is mounting observational evidence indicating how Ethiopia is highly vulnerable under both nonclimatic and climatic drivers. This paper addresses the water resources vulnerability of Ethiopia and presents an account of the observational evidence of the contextual vulnerability that may be considered representative of the greater Eastern Africa region composed of Somalia, Sudan, and Kenya.

5.21.2 Ethiopia in Eastern Africa: Climate and Water Resources

5.21.2.1 Location in East Africa

Eastern Africa is geographically divided in to three subregions, that is, Horn of Africa, which includes Ethiopia, Eritrea, Sudan, Djibouti, and Somalia; the Great Lakes region, which includes Uganda, Kenya, Tanzania, Rwanda, and Burundi; and the Indian Ocean islands of Comoros and Seychelles (**Figure 1**). The Horn of Africa has more desert and semidesert regions, whereas the Great Lakes region is known to have more forest area. The low-lying part of Northern Kenya and Somalia are relatively extremely dry, whereas the rainfall gain increases toward the south. Temperature in eastern Africa is generally moderate except in the hot and generally humid costal belts. Water availability is determined mainly by rainfall amounts. The amount of rainfall in Eastern Africa varies spatially and temporally. The Great Lake subregion receives more rainfall than the Horn of Africa. The rainfall amount varies seasonally as dry season, intermediate, and rainy season. Moreover, the rainfall has experienced an overall decline in Eastern Africa since the 1960s (Schreck and Semazzi 2004). This has caused periodic drought and thus water scarcity, which have resulted in famine in Eastern Ethiopia, Kenya, and Somalia land (USAID 2005; Cheung et al. 2008; USGS and USAID 2010).

Ethiopia is located almost at the center of the Horn of Africa (**Figure 1**) having a highly rugged landscape. The Great Rift Valley divides the country into the central/western highlands, which run from north to south, and the Eastern highlands (WAPCOS 1990). The highlands on each side give way to vast semiarid lowland areas in the east and southern part of the

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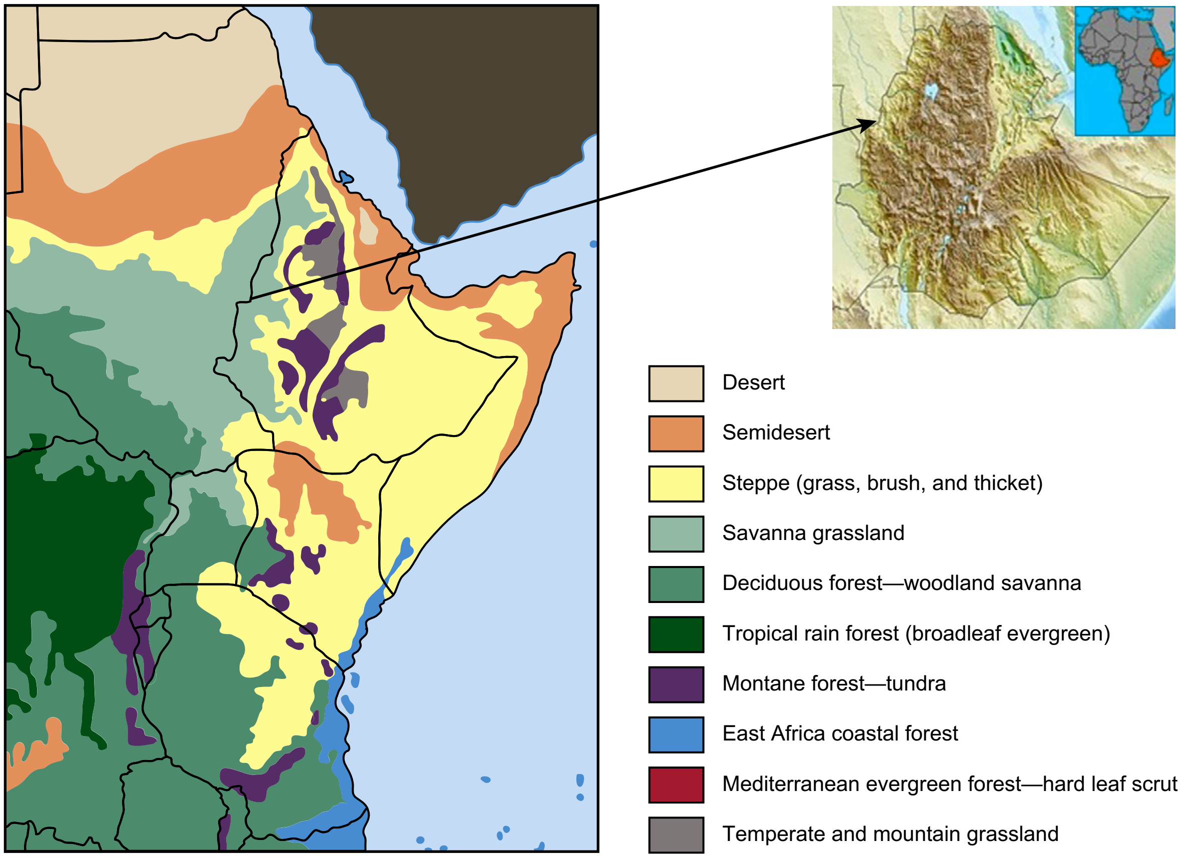

Desert
Semidesert
Steppe (grass, brush, and thicket)
Savanna grassland
Deciduous forest—woodland savanna
Tropical rain forest (broadleaf evergreen)
Montane forest—tundra
East Africa coastal forest
Mediterranean evergreen forest—hard leaf scrut
Temperate and mountain grassland

Figure 1 Location and relief map of Ethiopia.

country, exposing these areas to extreme climate variability and recurrent drought and famine.

5.21.2.2 Climate and Water Resources

Ethiopia has essentially a rainfed agricultural system where more than 83% of the population depends on subsistence agriculture. Although rainfall plays a great role as a vital water resource for securing nearly the entire food production of the country, the temporal and spatial distribution is extremely variable and uneven. The spatial mean annual rainfall distribution over the country varies above 2000 mm over some pocket areas in the southwest to less than 250 mm over the vast areas of Afar and Ogaden low lands in the eastern part of the country (NMSA 1996, 2001) (Figure 2). Most of Ethiopia receives between 50 to 100% of its annual rainfall during the rainy season from June to September during which 90% of food production is secured.

Studies estimate that the country has an estimated annual internal renewable water in the order of 122 billion cubic meters (BCM), excluding the groundwater potential from its 12 river basins (WAPCOS 1990). Groundwater contribution is believed to be in the order of 2.6 BCM. Less than 5% of the renewable water resources is put to any beneficial or strategic use in the country. The three river systems contributing to the Nile basin (Blue Nile, Baro–Akobo, and Tekeze), which comprise 30% of the total land areas, constitute nearly 70% of the total internally renewable water amount. The four major river basins originating from western highlands (the above-mentioned Nile tributaries and Omo–Gibe) constitute about 84% of the total volume of flow generated in Ethiopia. This is generated only from 38% of the total area of the country (western part). The remaining 62% of the country generates only 16% of the total internally renewable water. The main river basins that originate from the central and eastern parts of the country (Awash, Wabi-Shebelle, and Genale–Dawa) occupy about 43% of the country's area, but their combined runoff generation constitutes only 11% of the total runoff generated within the country. The Blue Nile river basin has the largest surface water generation with about 50 BCM of annual flow, followed by the Baro–Akobo and Omo–Ghibe basins. As shown in Figure 3 and Table 1, the water availability of the country is highly uneven and skewed to the western part of the country.

5.21.3 Historical and Observational Evidence of Climate Variability

The recent history of Ethiopia is remembered by the recurrence of hazardous droughts in many parts of the country (Shanko and Camberlin 1998; NMSA 2001; Funk et al. 2003; USAID).

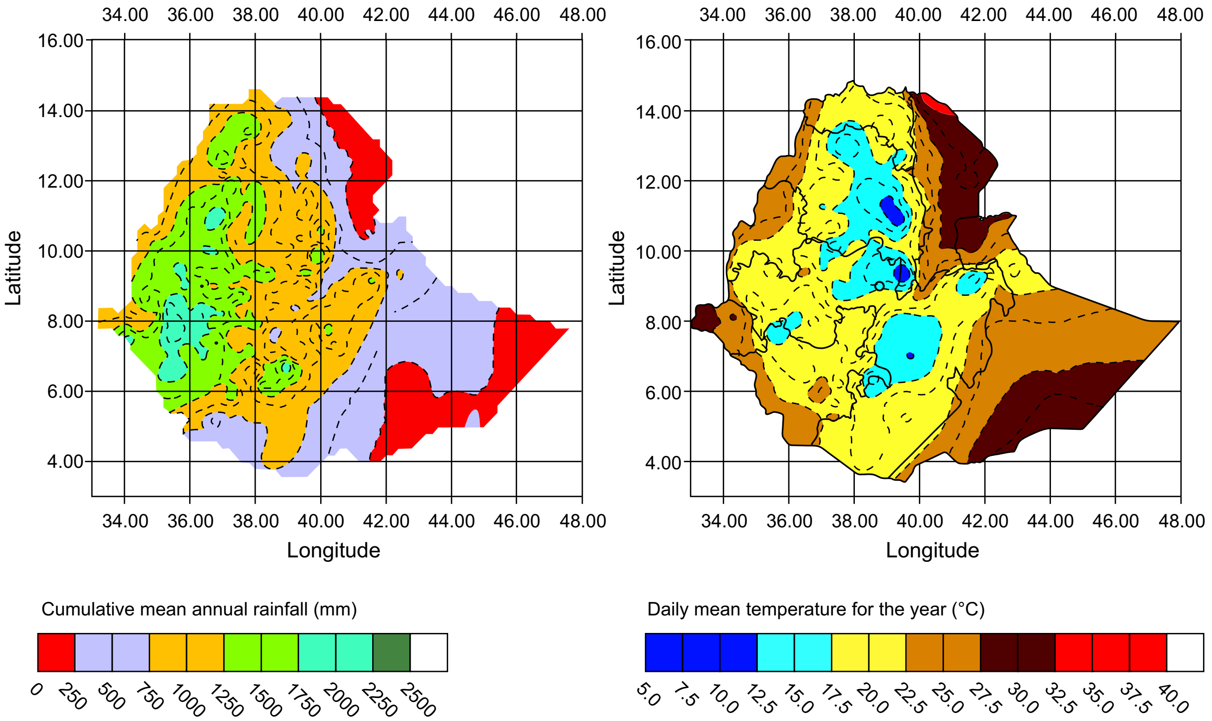

34.00 36.00 38.00 40.00 42.00 44.00 46.00 48.00
16.00
14.00
12.00
10.00
8.00
6.00
4.00
Latitude
Longitude
Cumulative mean annual rainfall (mm)
0 250 500 750 1000 1250 1500 1750 2000 2250 2500
Daily mean temperature for the year (°C)
5.0 7.5 10.0 12.5 15.0 17.5 20.0 22.5 25.0 27.5 30.0 32.5 35.0 37.5 40.0

Figure 2 Mean annual rainfall and temperature distribution over Ethiopia. NMSA (National Meteorological Service Agency), 2001: Initial National Communication of Ethiopia to the United Nations Framework Convention on Climate Change (UNFCCC) report. National Meteorological Service Agency, Addis Ababa, Ethiopia.

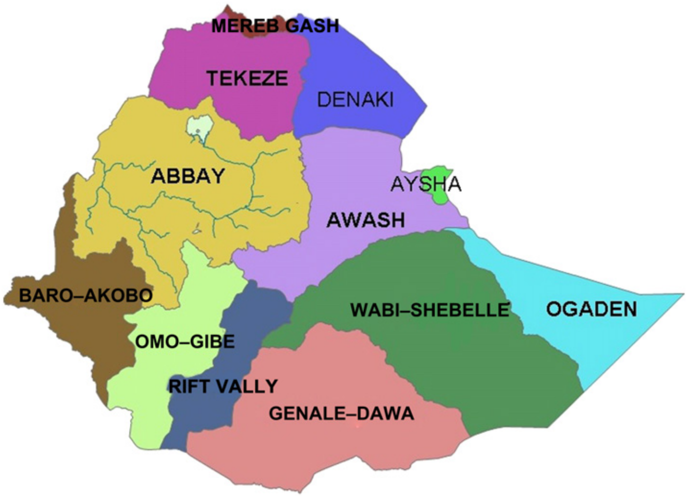

MEREB GASH
TEKEZE
DENAKI
ABBAY
AYSHA
AWASH
BARO-AKOBO
WABI-SHEBELLE
OGADEN
OMO-GIBE
RIFT VALLY
GENALE-DAWA

Figure 3 Major drainage basins of Ethiopia (refer **Table 1** for surface and groundwater resource potential).

Although the historical social and economic impacts of all these hazards are not systematically well documented, the impacts of the most important ones namely, droughts and floods, have been partially documented by Disaster Prevention and Preparedness Agency (DPPA) on NAPA (2007) since 1543 (Table 2). Catastrophic drought/famine has been recorded over the entire country, with major ones being concentrated in the northeast and southern part of the country. The frequency and magnitude of the occurrence has increased over time (NMA 2007). Actual figures indicate that the number of affected people has increased from 1.5 million in 1965 to over 13 million in 2002–03. Drought occurs anywhere in the world, but its damage is not as severe as in Africa in general and in Ethiopia in particular mainly because of low adaptive capacity (e.g., very few storage facilities).

The other climate-related hazards that affect Ethiopia from time to time are flash and seasonal river floods. Areas in the Afar region along the Awash river, in the Somali region

Table 1 Surface water resource of the major drainage basins of Ethiopia in reference to **Figure 3** for basins location

Basin name	*Area (km^2)*	*MAF (BCM)*	*GW (BCM)*
Blue Nile (Abbay)	199 812	52.6	1.8
Awash	112 700	4.6	0.14
Baro–Akobo	74 100	23.6	0.1
Genale–Dawa	171 050	5.8	0.03
Mereb	5700	0.26	–
Omo–Gibe	78 200	17.9	0.18
Rift Valley	52 740	5.6	0.01
Tekeze	89 000	7.63	0.2
Wabe–Shebelle	200 214	3.15	0.04
Afar–Danakil	74 000	0.86	–
Ogaden	77 100	0	–
Aysha	2200	0	–
Total	1 136 816	122	2.5

MAF, mean annual flow; GW, ground water; BCM, billion cubic meters.
Sources: Compiled from various river basin master plan studies WAPCOS, 1990: Preliminary Water resources development master plan for Ethiopia. Final report prepared for EVDSA, Addis Ababa, June. NMA, 2007: Climate Change National Adaptation Programme of Action of Ethiopia, National Meteorological Service Agency (NMSA). [Available online at http://unfccc.int/resource/docs/napa/eth01.pdf.] Accessed on 12 October 2011.

along the Wabi 26 Shebelle river and in the Gambela region along the Baro–Akobo rivers (Figures 1 and 3), in the southern region along the Omo–Gibe rivers, as well as the Bahirdar Zuria and Fogera areas along the Abbay river in the Amhara region are prone to seasonal river floods (Endalkachew et al. 2004; quoted in NMA p. 37). Major floods that caused loss of life and property occurred in different parts of the country in 1988, 1993–96, and 2006. For example, during the 2006 rainy season, flood caused a major disaster to life and property (NMA 2006). More than 250 people died, about 250 people were unaccounted for, and more than 10 000 people became homeless. In the south, more than 364 people died and more than 6000 people were displaced from about 14 villages because of flooding of the Omo river. Widespread flooding damage occurred in many parts of the country that had no past history of flooding. More than 16 000 people were displaced in West Shewa, while similar situations have been recorded in Afar, Western Tigray, Gambella Zuria, and the low-lying areas of Lake Tana. In terms of loss in property and livestock, the DPPA has estimated that over 199 000 people were critically affected. More than 900 livestock drowned over south Omo. A total of 2700 heads of cattle and 760 traditional silos were washed away (World Food Program, WFP). Over tenth of millions of dollars worth of property and infrastructure was destroyed by the flood that affected the Dire Dawa.

Observational evidence from historical records of temperature and precipitation spanning 1971–2000 for 42 selected stations (NMA 2007) shows that the country has experienced both dry and wet years. However, the overall trend of aerial average annual rainfall of the country has remained more or less constant (Figure 4). This implies that the aerial annual rainfall cannot be a proxy indicator of the extreme variability of rainfall over the eastern and northern parts of the country, indicating the divergent climatic situation of the country. For instance, the longer record available for the capital Addis Ababa (1898–2002) also shows no clear rainfall trends (Conway et al. 2004). Other stations in the Rift Valley not far from Addis Ababa exhibit declining trend, whereas stations toward eastern Ethiopia exhibit extreme

Table 2 Chronology of El Niño and drought/famine in Ethiopia

El Niño years	*Drought/famine*	*Regions affected*	*Impact on human life and property*
1539–41	1543–62	Hararghe	–
1618–19	1618	Northern Ethiopia	–
1828	1828–29	Shewa	–
1864	1864–66	Tigray and Gondar	–
1874	1876–78	Tigray and Afar	–
1880	1880	Tigray and Gondar	–
1887–89	1888–92	Ethiopia	–
1899–00	1899–00	Ethiopia	–
1911–12	1913-–14	Northern Ethiopia	–
1918–19	1920–22	Ethiopia	–
1930–32	1932–34	Ethiopia	–
1953	1953	Tigray and Wollo	–
1957–58	1957–58	Tigray and Wollo	–
1965	1964–66	Tigray and Wollo	About 1.5 million people affected
1972–73	1973–74	Tigray and Wollo	About 200 000 people and 30% of livestock dead
–	1978–79	Southern Ethiopia	1.4 million
–	1982	Northern Ethiopia	2 million people affected
1982–83	1983–84	Ethiopia	8 million affected 1 million dead and many livestock lost
1986–87	1987–88	Ethiopia	7 million people affected
1991–92	1990–92	North, Eastern, Southeastern Ethiopia	About 0.5 million people affected
1993	1993–94	Tigray and Wollo	7.6 million people affected
2000	–	Ethiopia	About 10.5 million people affected
2002–03	2002–03	–	About 13 million people were in need of food assistance

Source: NMA, 2007: *Climate Change National Adaptation Programme of Action of Ethiopia*. National Meteorological Service Agency (NMSA). [Available online at http://unfccc.int/resource/docs/napa/eth01.pdf.] Accessed on 12 October 2011.

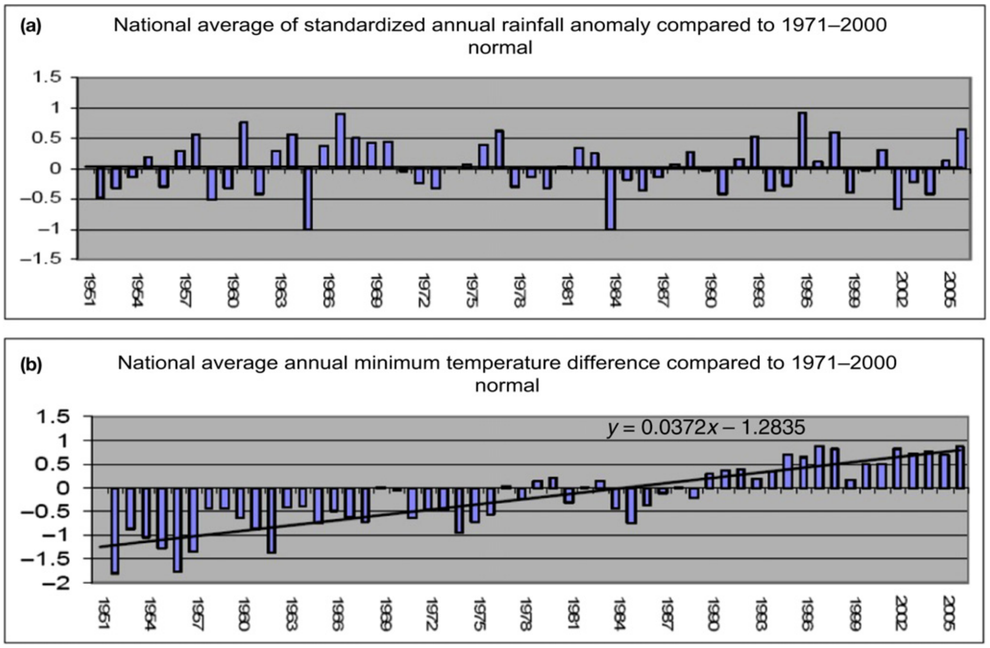


Figure 4 Year to year variability of annual rainfall and trend expressed in normalized deviation (a) and annual minimum temperature variability expressed in temperature difference (b) over Ethiopia. Source: NMA, 2007: *Climate Change National Adaptation Programme of Action of Ethiopia*, National Meteorological Service Agency (NMSA). [Available online at http://unfccc.int/resource/docs/napa/eth01.pdf.] Accessed on 12 October 2011.

variability (unpublished Awash hydrometerological report, 2012). Past studies have shown that there is a link between the El Niño and La Niña phenomena and the Ethiopian rainfall variability (Haile 1988; Korecha and Barnston 2007; Gissila et al. 2004).

The year to year variation of annual minimum temperatures expressed in terms of temperature differences from the mean and averaged over 40 stations (Figure 4) shows that the recent years are warmer compared to the early years. Overall, observation shows a warming trend of about 0.37 °C per decade. An unresolved issue, however, is explaining this trend. Candidates include added greenhouse gases (e.g., CO_2), which produces less radiative cooling at night (Steeneveld et al. 2011); regional landscape changes (Pielke et al. 2011); and deterioration of the spatial representativeness of the surface observing sites (e.g., Fall et al. 2011).

Such evidence from historical data does not, however, provide adequate information on the condition of the current vulnerability of Ethiopia. For instance, it has been documented by many researchers (e.g., Meze-Hausken 2004) that the observational record and the drought perception do not match the realities on the ground. As shown in Figures 5 and 6, the year 1979, which could be defined as a drought year in meteorological terms, was not regarded as such a drought year according to public perception. The year 1984 had a below-average total precipitation similar to the year 1979. However, 1984 'considered' a severe drought year, according to public perception (Figure 6). Therefore, it is believed that additional contextual factors (that are more 'bottom-up'), such as increase of rural population, and land degradation, resource vulnerability, poverty, etc. have likely contributed to this perception of the severity of a drought and dictated the population's resilience to it.

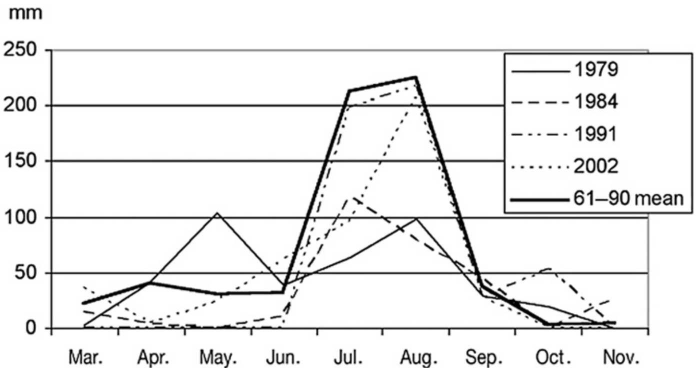


Figure 5 Annual rainfall record at Mekelle in Ethiopia during extreme drought years. The dark line is the mean annual rainfall record computed over 30 years. Source: Meze-Hausken, E., 2004: Contrasting climate variability and meteorological drought with perceived drought and climate change in northern Ethiopia. *Clim. Res.*, **27**, 19–31.

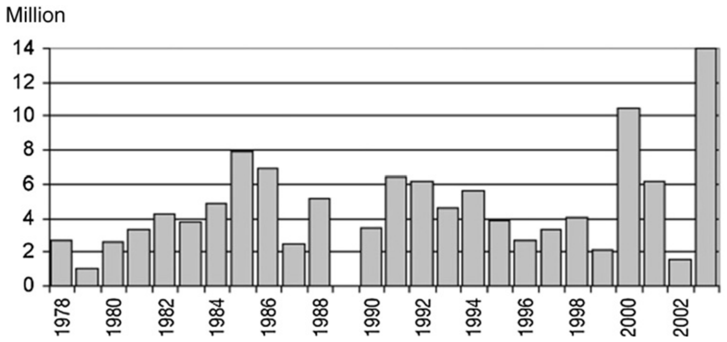
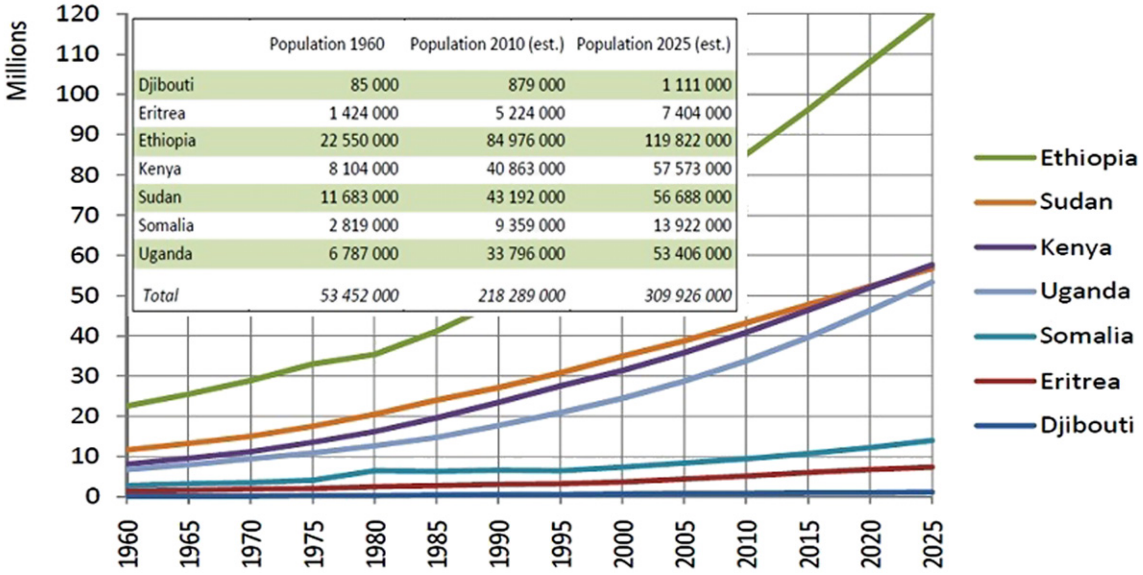


Figure 6 Number of people affected by natural disasters in Ethiopia after Meze-Hausken (2004).



	Population 1960	Population 2010 (est.)	Population 2025 (est.)
Djibouti	85 000	879 000	1 111 000
Eritrea	1 424 000	5 224 000	7 404 000
Ethiopia	22 550 000	84 976 000	119 822 000
Kenya	8 104 000	40 863 000	57 573 000
Sudan	11 683 000	43 192 000	56 688 000
Somalia	2 819 000	9 359 000	13 922 000
Uganda	6 787 000	33 796 000	53 406 000
Total	*53 452 000*	*218 289 000*	*309 926 000*

Figure 7 Population growth trend of eastern Africa. Source: van de Giessen, E., 2011: *Horn of Africa: Environmental Security Assessment*, Institute for Environmental Security, The Hague, The Netherlands (ISBN/EAN: 978-94-6055-005-8). [Available online at http://www.envirosecurity.org/espa/PDF/ESA_HOA.pdf.] Accessed on 03 February 2012 in reference to http://esa.un.org/unpp/.

5.21.4 The Contextual Vulnerability Factors

5.21.4.1 Population Growth and Multidimensional Poverty

The Eastern Africa population is continuously growing with the annual growth rate greater than 2.2%. According to the United Nations Development Programme (UNDP), the 2011 Human Development Index (HDI) reported that Ethiopia is the second populous country in the continent and has a population of 85 million as of 2011. This population is projected to become about 120 million by 2030. More than 83% of the population is rural and lives largely as subsistence rainfed agricultural farmers. About 88% of the population is affected by multidimensional poverty, of which about 72% live under severe poverty (UNDP-HDI Office 2011) (Multidimensional poverty index (MPI) is a weighted poverty index that integrates the indicators of deprivations of education, health, and living standard. Each indicator carries 1/3 weight (UNDP-HDI Office, 2011)). Figure 7 shows the regional population of Eastern Africa reaching to over 300 million by 2025 (van de Giessen 2011). This adds additional pressure on land and water resources of the region, and the population remains more vulnerable than ever to the natural shocks from climate variability.

A study conducted by Deressa et al. (2008) examined indicators of vulnerability across 7 of the 11 Regional States of Ethiopia: Afar; Amhara; Beneshangul Gumuz; Oromia; the Southern Nations, Nationalities, and People's Region (SNNPR); Somali; and Tigray (Figure 8). The study calculated vulnerability to climate by region as the net effect of sensitivity, exposure, and adaptive capacity. Results indicate that Afar, Somali, Oromia, and Tigray are relatively more vulnerable to climate than the other regions. The vulnerability of Afar and Somali (eastern part of Ethiopia) is attributed to their low level of rural service provision and infrastructure development. Tigray and Oromia's vulnerability to climate can be attributed to the regions' higher frequencies of droughts and floods, lower access to technology, fewer institutions, and lack of infrastructure. SNNPR's lower vulnerability is associated with the region's relatively greater access to technology and markets, larger irrigation potential, and higher literacy rate (Figure 8).

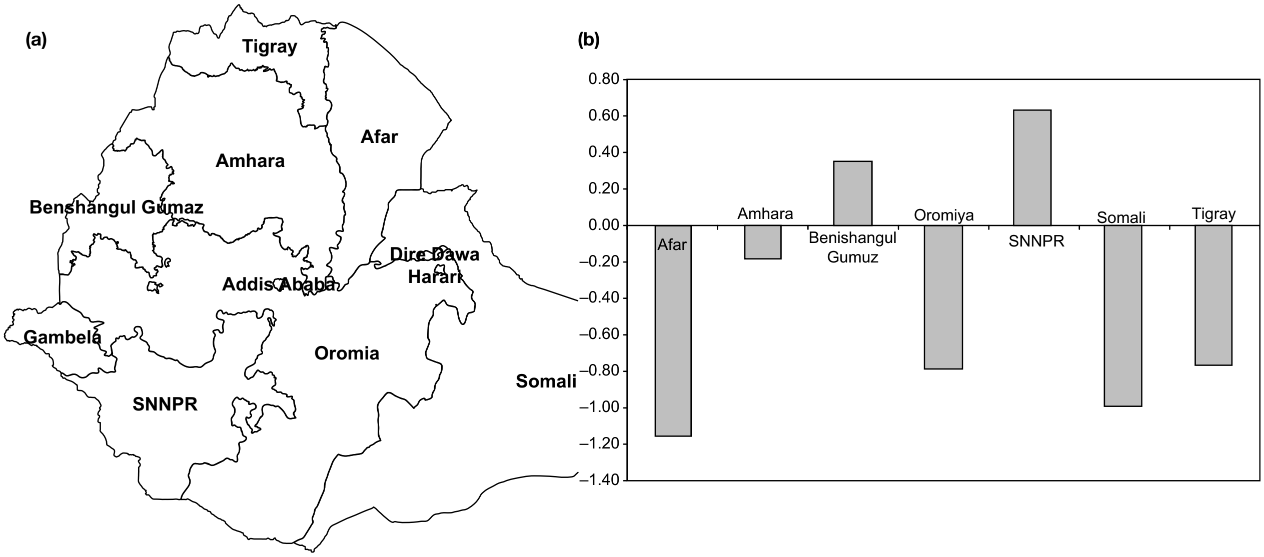


Figure 8 (a) The spatial vulnerability of the seven main regional states of Ethiopia. The negative *y*-axis in (b) represents the ‘vulnerability’ index with 0 being no vulnerability. Positive *y*-axis means negative vulnerability or positive resilience. Reproduced from Deressa, T. T., R. M. Hassan, and C. Ringler, 2008: Measuring Ethiopian farmers’ vulnerability to climate change across regional states. International Food Policy Research Institute (IFPRI) Discussion Paper, 00806, Washington, DC. [Available online at http://www.ifpri.org/sites/default/files/publications/ifpridp00806.pdf.] Accessed on 15 August 2011.

5.21.4.2 Dependence on Rainfed Agriculture

As mentioned earlier, an estimated 83% of the population is dependent on rainfed agriculture and lives in rural areas. Agriculture employs 80% of the labor force and accounts for 50% of the GDP. When the resources base (which is rainfall) gets degraded because of climate and hydrological variability, manifested as dry spells, droughts, and floods, a profound impact on the production of agriculture has been noted. Consequently, the entire population has become vulnerable to food insecurity (famine). The destructive nature of droughts and floods is now becoming endemic with increasing occurrence compared to four decades ago because of the low adaptive capacity. In terms of economic cost that World Bank estimates show, one-third of the economic gains can easily be lost through the impacts of hydrological variability (Figure 9). Generally, water as a natural resources base for food production is tied up with subsistence level farming (usually farmlands less than 1 ha). Almost everybody produces his/her own food as well as food for the few additional urban residents. Therefore, the complex relationship of water–food nexus is highly fragmented and requires an adaptation approach that is highly flexible and contextual.

5.21.4.3 Land Degradation and Desertification

Land degradation here mainly refers to the loss of life-supporting land resource through soil erosion, desertification,

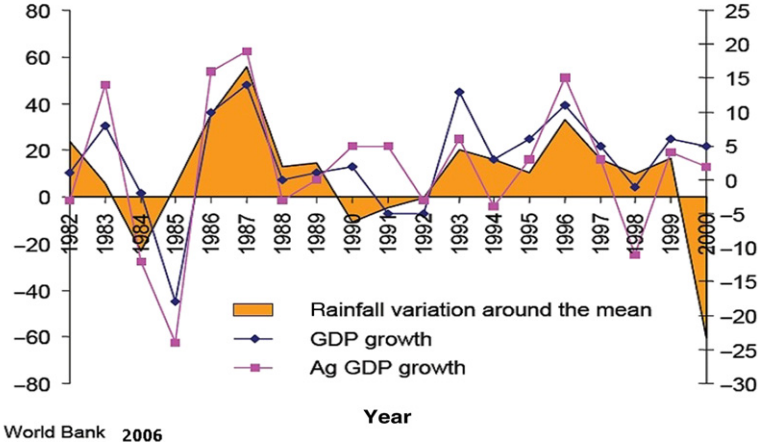
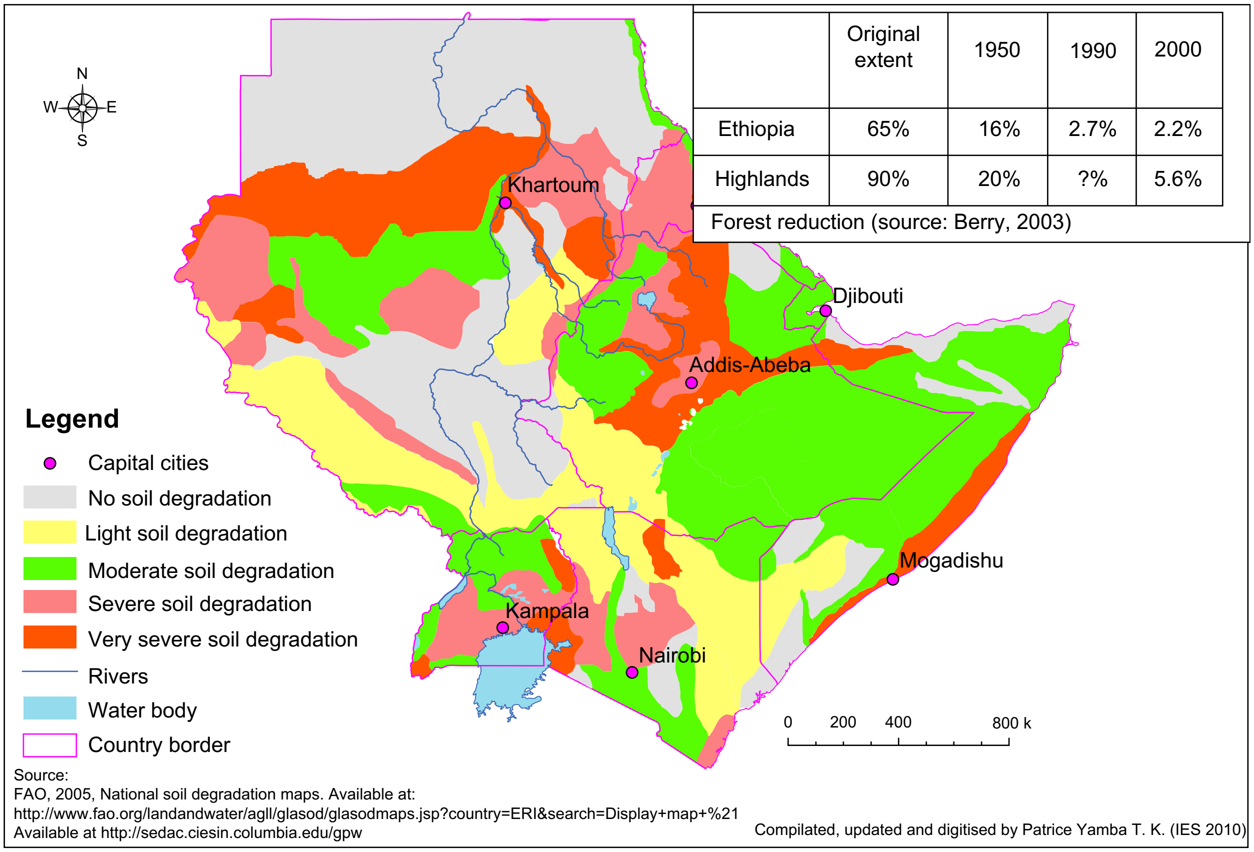


Figure 9 Rainfall, GDP, and agricultural GDP (Ag GDP) of Ethiopia. Reproduced from World Bank, 2006: Managing Water Resources to Maximize Sustainable Growth: A Country Water Resources Assistance Strategy for Ethiopia. The International Bank for Reconstruction and Development, Washington, DC, http://siteresources.worldbank.org/INTWRD/Resources/Ethiopia_final_text_and_cover.pdf. Accessed on 02 February 2012.



	Original extent	1950	1990	2000
Ethiopia	65%	16%	2.7%	2.2%
Highlands	90%	20%	?%	5.6%

Forest reduction (source: Berry, 2003)

Source:
FAO, 2005, National soil degradation maps. Available at:
http://www.fao.org/landandwater/agll/glasod/glasodmaps.jsp?country=ERI&search=Display+map+%21
Available at http://sedac.ciesin.columbia.edu/gpw

Compiled, updated and digitised by Patrice Yamba T. K. (IES 2010)

Figure 10 Soil degradation map of eastern Africa. Source: http://www.envirosecurity.org/espa/horn-ofafrica/maps_images.php

salinization, acidification, etc. Deforestation accounts for the major land degradation problem as it results in severe soil erosion, flood, and loss of fertile soil. Eastern Africa including Ethiopia has experienced moderate to severe land degradation problems as shown in Figure 10. The figure shows that very severe degradation occurred in northern Ethiopia (the food basket area), Sudan, and part of Somalia. For instance, over a period of time, Ethiopia's original forest cover was reduced from 65% to a mere 2.2% of the total country's area coverage (Berry 2003). This has resulted in reduction of soil water holding capacity of the known spring water sources and base flow of streams, which are known to be vital sources of residual soil moisture and domestic water sources. Desertification, on the other hand, generally occurs after a prolonged degradation of land. Desert areas cannot support life for long as the available water can hardly support life. Farmers in Ethiopia, Somalia, and Kenya are therefore more vulnerable to undergoing desertification than others.

5.21.5 Bottom-Up Adaptation Approaches to Climate Vulnerability

5.21.5.1 The Proposed Adaptation Action Plan

Adaptation to climate variability is now one the main theme for African nations. It has been shown that many countries in the continent have developed National Adaptation Programmes of Action (NAPAs). Most of these NAPA documents have direct reference to the coarse-scale IPCC global climate change projections output, and reference to the local situation is very limited. Consequently, most of the recommended adaptation options neither provide location-specific contextual adaptation options geared to the local situations nor consider that the IPCC global climate change projections have not demonstrated any skill at predicting *changes* in regional climate statistics (Pielke et al. 2012). For instance, the NAPA adaptation recommendations for Ethiopia provided a mix of 26 potential adaptation options before even classifying the vulnerable resources, the type of vulnerability, and priority area of specific adaptation sites. It is true that most of the climate-related vulnerabilities will likely affect the entire country and that the national recommendation may subscribe to many of the 26 recommended adaptation options (Table 3).

However, the productive area of Lake Tana subbasin in the northeastern part of Ethiopia is more vulnerable to flash floods than drought. It requires specific adaptation solution of flood protection, flood early warning system, rather than drought mitigation options per se. Therefore, such kind of local-scale qualification of the priorities is required further in Ethiopia. In this case, the bottom-up adaptation approach is more realistic as it provides specific, cost-effective, and at site adaption options that can provide measureable solutions and framework for studying the interaction of resources with the society locally.

Table 3 Recommended adaptation measures for Ethiopia

Serial number	*Specific adaptation measures*
1	Promoting drought/crop insurance program in Ethiopia
2	Realizing food security through multipurpose large-scale water development project in Gennale Dawa basin
3	Community-based development and commercialization of nontimber forest products (gum Arabic, myrrh, and Frank incense)
4	Community-based rehabilitation of degraded ecosystems in selected parts of Ethiopia
5	Propagation and commercial-scale cultivation of wild essential oil crops
6	Establishment of center for propagation and commercialization of traditional herbal medicinal plants
7	Establishment of acacia woodland nature reserve in the Ethiopia rift valley system
8	Community-based carbon sequestration project in the rift valley system of Ethiopia
9	Range shift cultivation of selected cash crops in drought-prone areas
10	Establishment of national research and development center for climate change
11	Development of an incentive scheme for farmers (hill-farming communities) to restore hill areas in the northern part of Ethiopia
12	Participatory approach to rehabilitate degraded hills/ecosystems in northern Ethiopia
13	Institutional reenforcement for biodiversity conservation
14	Establishment of national environmental education program
15	Reforestation for fuel in the highlands of Ethiopia
16	Regional capacity building for monitoring and inventorying of biodiversity
17	Establishment of potato-centered small-sized cottages
18	Reclamation of bush-encroached rangelands
19	Promotion of legume-based agroforestry systems and home garden agriculture
20	Development of new and rehabilitation (upgrading) of the existing watering sites in pastoral areas
21	Aquaculture development for efficient harvest of commercial *Spirulina* sp. in the lake of Ethiopian rift valley system
22	Reorganization of drought-affected communities
23	Stall feeding promotion and free range grazing restriction on selected regional states of Ethiopia
24	Promotion of on-farm and homestead forestry and agroforestry practices in arid, semiarid, and dry subhumid parts of Ethiopia
25	Undertake soil and water conservation practices for improving land husbandry in Afar, Somali, and Gambella regional states and Dire Dawa city administration
26	Develop community seed bank and food storage facilities in Amhara, SNNPRS, Tigray, and Oromia

Source: NMA, 2007.

5.21.5.2 A Paradigm Shift in Climate Adaptation in Ethiopia

5.21.5.2.1 Implementation of Water Storage Continuum

In Ethiopia, like other Eastern Africa countries, the economy and livelihood of the society is highly correlated with rainfall variability. Compounded with the level of poverty, demographic rise, and low level of adaptive capacity and resilience, there is now no doubt that an adaptation option in Ethiopia and Eastern Africa will be the best approach that dampens the impact of rainfall variability through storing water in available storage media whether as soil moisture storage, ponds, or dams. There is huge potential to rethink access to water availability of water storage in all places and at scale commensurate to the relevant factors of topography, climate, hydrology, and soil. Ethiopia is one of the countries with the lowest per capita water storage availability in the world with 43 m^3 per capita, in contrast to 750 m^3 per capita in South Africa and about 6150 m^3 per capita in the United States (World Bank 2006). This underscores the necessity of building storage facilities across the nation. This requires understanding the storage development niche of each area and of the variety of storage options with regard to climate, topography, hydrology, and capacity.

Johnston and McCartney (2010) have provided a paradigm for natural as well as artificial storage as a continuum of storage facilities to be implemented as a bottom-up adaptation option. The storages include a variety of forms incorporating small-scale soil moisture storage through water harvesting ponds to large-scale water storages (such as small to large dams): natural wetlands, soil moisture, groundwater aquifers, ponds/small tanks, and reservoirs (Figure 11). There appears no other way, other than introducing such strategic storage options, to reduce the vulnerability of the water resources in Ethiopia. Especially, the untapped surface water resources, which are estimated to be in the order of 122 BCM, can be a buffer to offset the increasing variability of food and water insecurity in Ethiopia.

5.21.5.2.2 Social Protection Schemes: Productive Safety Net Programme (PSNP)

The identification of the type of storage requirement and its implementation will require time. In the interim, social protection schemes are vital as a transition mechanism to help societies adapt to newer approaches. There is already a functioning social protection scheme in Ethiopia called Productive Safety Net Program (PSNP) as a transitory mechanism (Devereux and Guenther 2007). PSNP is the largest social protection scheme in Africa outside of South Africa's social grants schemes. The PSNP delivers social transfers to some 8 million Ethiopians each year, either through 'public works' activities or as 'direct support' for households that are labor constrained. Capitalizing on the public works component, social protection schemes can be used to involve the productive labor force in building community assets used for adaptation purposes such as water harvesting structures, tree planting, and water and soil conservation activities. There is already an

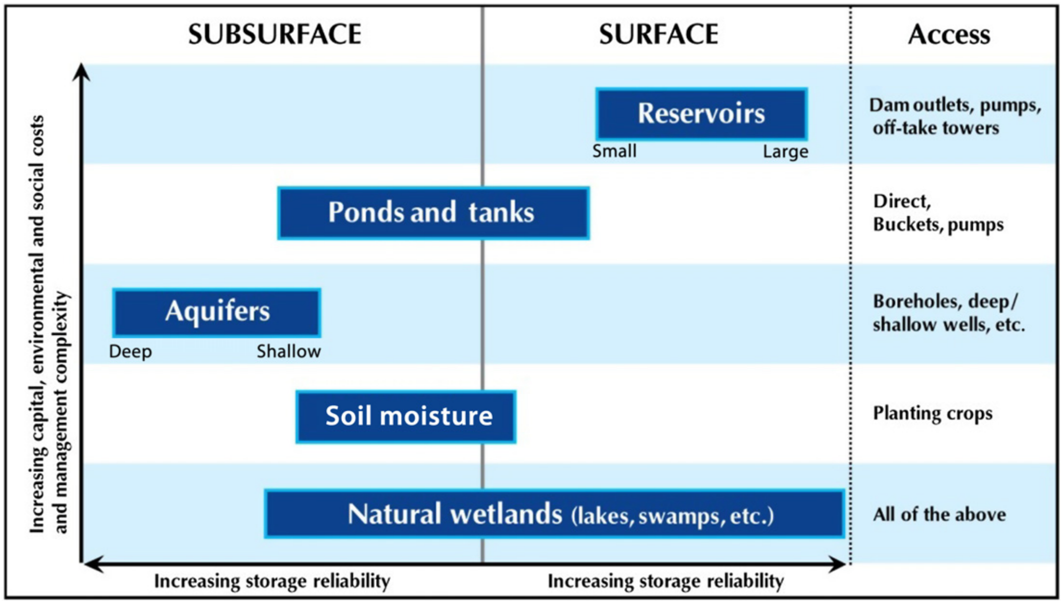

SUBSURFACE
SURFACE
Access
Increasing capital, environmental and social costs and management complexity
Reservoirs
Small
Large
Dam outlets, pumps, off-take towers
Ponds and tanks
Direct, Buckets, pumps
Aquifers
Deep
Shallow
Boreholes, deep/ shallow wells, etc.
Soil moisture
Planting crops
Natural wetlands (lakes, swamps, etc.)
All of the above
Increasing storage reliability
Increasing storage reliability

Figure 11 Water storage continuum. Source: McCartney, M. and I. Eguavoen, 2010: Re-thinking water storage for agricultural adaptation to climate change in Sub-Saharan Africa. Tropentag 2010 conference on International Research on Food Security, Natural Resource Management and Rural Development, Zurich, September 14–16, 2010. [Available online at http://africastorage-cc.iwmi.org/Data/Sites/25/media/PDF/.] Accessed on 1 September 2011.

encouraging sign in northern Ethiopia that natural springs have started to reappear, water and soil conservation structures have yielded moisture enhancements, and farmers have been reported to graduate from the social protection schemes. Therefore, social protection schemes are suggested as a bridge to building adaptation assets in chronically moisture-constrained areas of southeastern, eastern, and northern parts of Ethiopia.

5.21.5.2.3 Weather-Indexed Drought Insurance

Ethiopian smallholders face persistent risks of drought, against which they are unable to insure, because of missing insurance markets. According to a review by Devereux and Guenther (2011), experience from other countries suggests that insurance delivers both social protection for farmers (a guaranteed safety net against harvest failure) and agricultural growth (confidence to take moderate risks such as investing in fertilizer or high-yielding varieties). Missing insurance markets is a common feature throughout Africa and is explained by such factors as low incomes of farming households, information asymmetries, moral hazard, and the covariate nature of agricultural risks. Therefore, it is suggested that drought insurance be implemented not as a stand-alone blanket measure to reduce drought vulnerability, but in areas where mild to moderate drought occurs and productivity is high. This can protect the main base of the food basket of the country during the national drought periods.

5.21.5.2.4 Extreme Hydrological Events, Forecasting and Early Warning Systems

Institutionalized forecasting and early warning system is one of the technological options that can be implemented in the region. There is evidence of preparedness and reduction of catastrophes in the flood and drought areas of the region as a result of forecasting and early warning system. Thus, investing in such early warning systems can be incorporated as part of adaptation package that covers from small-scale to large-scale water resources vulnerability reduction. It can be used to forecast large-scale drought for rainfed agriculture to inflow forecasting for reservoir operation for hydropower and irrigation systems in the region.

5.21.6 Conclusion

Historical evidence shows that the eastern parts of Africa are highly vulnerable to the impact of variability from climate. Most parts of Ethiopia, in particular, have experienced pronounced effects of drought over the past 40 years. The nonclimatic drivers such as population explosion, land and water degradation, etc. collectively expose the country further to vulnerability.

Recent studies also show that the region is highly sensitive to changes in precipitation and temperature. Investigations reveal that a 1-unit change to precipitation variability can significantly affect the freshwater availability by about 2 units. Such high sensitivity of precipitation to fresh water supply is another critical dimension of climate vulnerability of the region. With respect to the future, it currently remains highly uncertain as to what should be the most effective adaptation strategy to address these vulnerabilities.

Compounded with the level of poverty and population rise, the best adaptation option in Ethiopia and eastern Africa is to improve adaptive capacity and resilience to vulnerability through strategic storage of water through soil moisture storage, artificial reservoirs, and groundwater. There is a huge potential if water storage is addressed in the continuum of the scale from soil water storage to large-scale reservoir storage commensurate to the relevant factors of topography, climate, hydrology, and soils. Ethiopia is a country with the a water storage availability of 43 m^3 per capita in contrast to 750 m^3 per capita in South Africa and about 6150 m^3 per capita in the United States. This underscores the necessity of building strategic storage facilities across the region. A paradigm shift toward protection of the community through such insurance schemes for drought and flood damages is a highly recommended option. Other options such as forecasting and early warning system of seasonal extreme hydrological conditions may be integrated in the overall adaptation strategies. This chapter has overviewed the contextual issues of water resources vulnerability and suggested a way forward for policy makers and planners.

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5.22 Hydroclimatology and Large-Scale Population Vulnerability to Cholera Outbreaks in the Bengal Delta

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5.22.1 Introduction

5.22.1.1 Seasonal and Spatial Asymmetry

The highly populated coastal floodplains of the Bengal Delta have a long history of water-related natural calamities such as droughts, floods, and cyclones. These events have often been followed by waterborne epidemic outbreaks in coastal as well as inland areas. The diarrheal disease outbreaks in the Bengal Delta, such as cholera, rotavirus, and dysentery, show distinct seasonal peaks and spatial signatures in their origin and progression. However, the mechanisms behind these seasonal phenomena, especially the role of regional climatic and hydrologic processes behind the disease outbreaks, are not fully understood.

The Ganges–Brahmaputra–Meghna (GBM) river system, the third largest freshwater flow regime in the world, flows through the Bengal Delta region to the Bay of Bengal (BoB). The system is composed of two of the largest Himalayan rivers, the Ganges and the Brahmaputra, which are subsequently joined by Meghna in Bangladesh. Most of the annual precipitation in this basin region occurs during the four monsoon months, June–September (Chowdhury and Ward 2007). The lowest flows in the Brahmaputra and the Ganges are recorded during January–April and are typically one-tenth and one-twentieth of the average peak flows in respective rivers. Such drastic reductions cause a drop in the hydraulic head of the GBM system and its tributaries, which aids salt-water intrusion from the coast toward the inland freshwater resources (Rahman et al. 2000), which has significant impacts on available water for agriculture and domestic consumption, ecosystem, and public health (Miller et al. 1982; Wahid et al. 2007; Mirza 2011). The lower parts of the Bengal Delta, especially southwestern Bangladesh, are affected more during this season, when cholera outbreaks are seen in the southern coastal districts (Alam et al. 2006; Akanda et al. 2011) (Figure 1).

The rivers rise rapidly as monsoon rainfall arrives in June (Ahmed and Karmakar 1993) and reach peak flow levels during August–September (Mirza 2011). The entire country is situated on low-elevation alluvial floodplains and prone to flooding by the GBM system at its peak level. About 20% land area of Bangladesh is annually inundated on average; more than 60% in high flood years (Chowdhury and Ward 2007). However, majority flooding takes place in the central and eastern floodplains of Bangladesh. Open mixing of water between sewers, exposed drains, reservoirs, and rivers during floods quickly contaminates the submerged areas with infectious pathogens from other infected water sources. Islam et al. (2006) identified that 62.5% of water samples were infected with the cholera bacteria in suburban reservoirs of Dhaka during the 2004 floods. Water levels on adjoining low-level flood plains may stay inundated till November because of low gradients and congested drainage and serve as ideal habitats for harmful vibrios such as *Vibrio cholerae* even after the flood recedes and act as sources of infection for the surrounding population (Schwartz et al. 2006).

5.22.1.2 Spatiotemporal Characteristics of Cholera Incidence

Cholera, an acute infectious diarrheal disease caused by the bacterium *V. cholerae*, has reemerged as a global public health issue in recent decades. The world has seen an unprecedented rise in cholera infection and transmission since the 1990s, with recent outbreaks across three continents, in Pakistan, Nigeria, and Haiti (Akanda et al. 2012). Cholera records typically show single annual peaks in most affected areas, such as parts of Africa, Southeast Asia, and Latin America (Hashizume et al. 2008). However, the GBM delta region of the Indian

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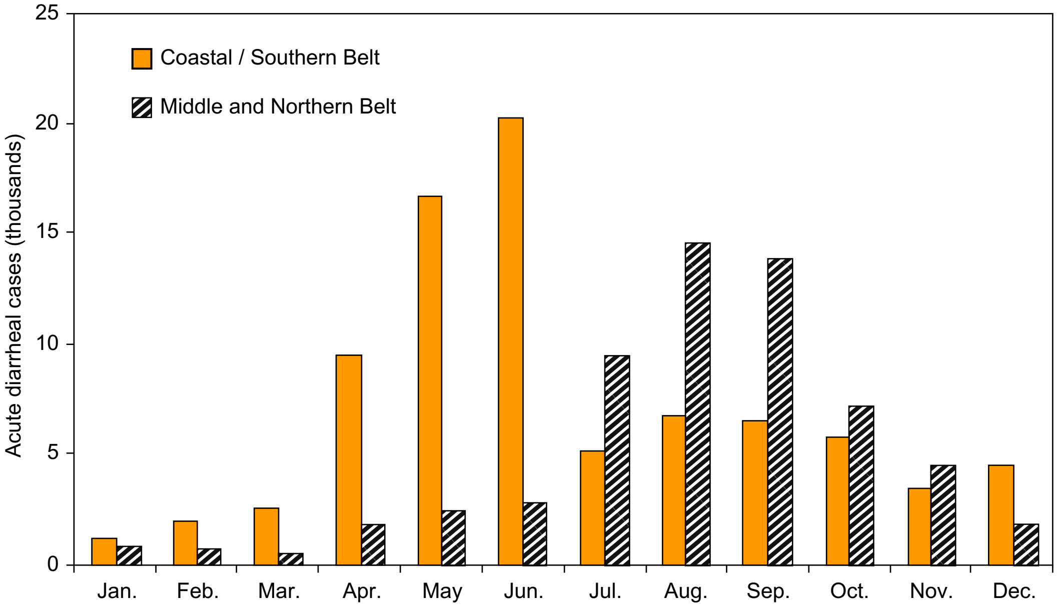

Figure 1 Average monthly acute diarrheal infection observed in the southern (coastal) and northern (middle/inland) areas of Bangladesh, 1995–2000. Source: Akanda, A.S., Jutla, A.S., Alam, M., Constantin de Magny, G.C., Siddique, A.K., Sack, R.B., et al. 2011: Hydroclimatic influences on seasonal and spatial cholera transmission cycles: implications for public health intervention in Bengal Delta. *Water Resour Res.*, 47, W00H07, doi: 10.1029/2010WR009914.

subcontinent shows distinct biannual peaks in central floodplain regions, spring peaks in coastal areas, and fall peaks in inland floodplains (Sack et al. 2003; Akanda et al. 2011). A coupled analysis of the regional climatic processes and cholera surveillance data reveals a strong association of the significant outbreaks with seasonal climatic processes and extreme events. In addition, evidence suggests that cholera outbreaks are propagated from coastal to inland areas and from spring to fall influenced by two distinct, pre- and postmonsoon, hydroclimatic processes (Akanda et al. 2011).

The cholera surveillance program at the International Center for Diarrheal Disease Research, Bangladesh (ICDDR,B) provides some of the longest and largest records available in the world (Longini et al. 2002). The program carries out systematic subsampling of all patients visiting the hospital through laboratory tests to confirm *V. cholerae* infection. The cholera incidence patterns in the Bengal Delta region exhibits significant seasonal and interannual variability, revealing the association of the spring cholera outbreaks with the low flow season of the GBM rivers. Cholera incidence decreases during peak monsoon months (June–September) but starts increasing again in later monsoon, with a larger second peak in October and November (Schwartz et al. 2006). More spring outbreaks are typically seen in coastal districts, whereas fall outbreaks are typically seen in central and northeastern Bangladesh (Akanda et al. 2011). For example, Mathbaria, a coastal area near the coast of BoB experiences cholera outbreak peaks only during March–May, whereas Chhatak in the northeastern corner of the country typically observes late fall peaks (Figure 2).

Cholera epidemics in Bangladesh have been previously linked to a range of climatic and environmental variables such as sea surface temperature (SST) and sea surface height (SSH) (Lobitz et al. 2000), plankton abundance (de Magny et al. 2008; Emch et al. 2008), precipitation (Hashizume et al. 2008), floods (Koelle et al. 2005), peak river level (Schwartz et al. 2006; Emch et al. 2008), salinity (Miller et al. 1982), and fecal contamination (Islam et al. 2006). However, most of the above-mentioned studies tried to explain the dual-peak outbreaks with single-peak environmental variables, and thus the relationships between underlying hydroclimatic and environmental processes and biannual cholera incidences in Bangladesh, and also the asymmetry in spatial distribution of cholera outbreaks are not understood well. More specifically, how these large-scale processes initiate or propagate cholera outbreaks in different areas of the Bengal Delta and how the seasonal and interannual variability of cholera incidence show distinct spatial signatures at different hydrologic regimes are not known. The following sections in this chapter will attempt to identify the key hydrologic, climatic, and environmental processes that are known to play crucial roles in cholera transmission and provide a detailed understanding of the role of the hydroclimatic extremes and resulting population vulnerability to cholera outbreaks.

5.22.2 Key Hydroclimatic and Environmental Processes

5.22.2.1 The Concept of Seasonal and Spatial Transmission Cycles

Cholera broke out as part of a global pandemic in the Bengal Delta region of the Indian Subcontinent during the early nineteenth century (Sack et al. 2004). About 200 years later, the disease still remains a major threat to public health in the

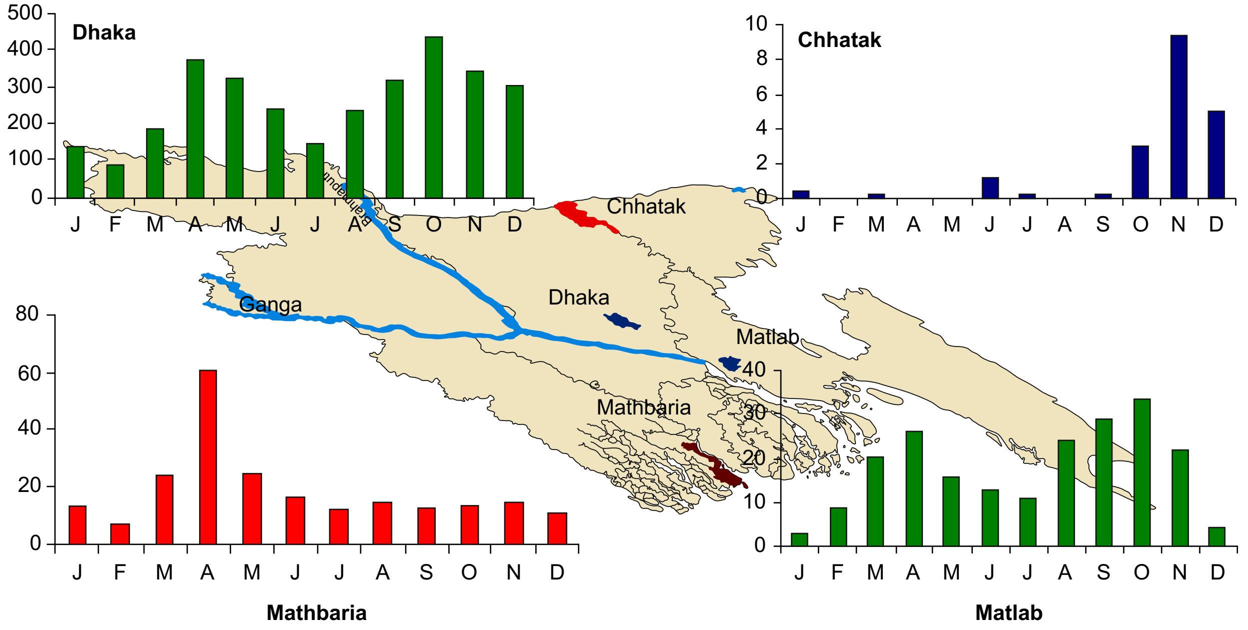

Figure 2 Monthly climatology of cholera incidence recorded at ICDDR,B surveillance centers in Dhaka, Mathbaria, Chhatak, and Matlab, Bangladesh. Source: Akanda, A.S., Jutla, A.S., Alam, M., Constantin de Magny, G.C., Siddique, A.K., Sack, R.B., et al. 2011: Hydroclimatic influences on seasonal and spatial cholera transmission cycles: implications for public health intervention in Bengal Delta. *Water Resour Res.*, 47, W00H07, doi: 10.1029/2010WR009914.

developing world. Cholera is an acute waterborne diarrheal illness caused by two toxigenic strains of the bacterium *V. cholerae*, O1 and O139, which are associated with marine plankton species (Colwell and Huq 2001). There is agreement on the coastal nature of early outbreaks of this infectious disease however, the striking seasonality and strong interannual variability as well as its annual recurrence and spatial variability in endemic areas remain a mystery to scientists and public health professionals Jutla et al. 2010).

For the past several decades, cholera research has primarily focused on clinical, microbiological, and ecological aspects of the bacterium, including vaccines, therapy, and improved treatment. The role of underlying hydrologic, climatic, and other large-scale environmental processes in transporting cholera bacteria through the ecosystem and propagating the disease in different seasons has received less attention (Jutla et al. 2010). Earlier studies related to cholera outbreaks in Bengal have mostly focused on rural areas (Cockburn and Casanos, 1960; Glass et al. 1982; Bouma and Pascual 2001). In fact, an overwhelming fraction of the investigations on cholera outbreaks (Longini et al. 2002; Ruiz-Moreno et al. 2010) and the role of environmental factors (Koelle et al. 2005; Emch et al. 2008; de Magny et al. 2008) have relied on surveillance data from Matlab. Also, these studies did not attempt to explain how large-scale drivers (e.g., precipitation, flood, temperature) with single annual peaks create dual seasonal peaks in cholera incidence.

Siddique et al. (1994) was perhaps the first study to suggest plausible pathways of the progression of cholera outbreaks from the coastal regions of Bangladesh to the inland areas of the country during major epidemics. A more recent study, by Sack et al. (2003), showed that spring peaks are more common in locations closer to the coast, whereas the inland locations are affected mostly by fall outbreaks. Taken together, these studies suggest a spatial heterogeneity of cholera outbreaks across the Bengal Delta region. Akanda et al. (2011) showed that same-year seasonal cholera outbreaks are also strongly correlated, but the seasonal correlation broke down between successive years between 1980 and 2007. An intriguing finding of this analysis is that summer and fall prevalence are dependent on preceding spring outbreaks; however, fall outbreaks do not have an impact on subsequent spring prevalence, suggesting a break in transmission during winter.

Jutla et al. (2010) previously argued that coastal plankton abundance in the BoB and the associated saltwater and vibrio intrusion during the dry season (January–April) may initiate early cholera outbreaks in the GBM Basin. On the other hand, as the streamflow direction is predominantly southward in regional rivers during and after the monsoon season (June–November) (Mirza 2011), there would be no realistic way for coastal plankton to reach estuarine rivers during these months. If coastal plankton abundance, salinity, and associated bacteria affect inland water resources only during spring, and if summer and fall prevalence are dependent on the preceding spring outbreaks, one would expect to see a physically consistent pattern of prevalence in regions affected by coastal intrusion.

Figure 1 shows the monthly average number of cholera cases recorded at each of these four locations. The spatial and temporal patterns of cholera incidence suggests that coastal hydroclimatic processes primarily modulate the first outbreak season in spring, whereas inland processes exhibit a strong influence on the second cycle of outbreaks. Mathbaria, a coastal location close to the BoB, shows cholera outbreaks during the dry season, whereas Chhatak shows outbreaks only during the fall months following the monsoon season. Dhaka and Matlab, located in the floodplain corridors of the GBM rivers, are affected by both outbreaks.

Another interesting observation of the above-mentioned studies is that monsoon rainfall in the region also shows a consistently positive relationship with summer and fall cholera prevalence (Akanda et al. 2011). As streamflow is an aggregated measure of rainfall, it is expected that precipitation would exhibit a positive influence similar to that of streamflow (Akanda et al. 2009). However, as the arrival, duration, and intensity of monsoon rainfall, as well as the terrain and topography, can widely vary over the 1.5-million-km^2 GBM Basin (Chowdhury and Ward 2007; Ahmed and Karmakar 1993), and as the vast majority of water arrives from upstream regions (Mirza 2003), the role of monsoon rainfall in the contamination of water resources inside Bangladesh may actually be limited compared to that of large-scale flooding in the GBM Basin region due to flow from upstream. This assertion is also validated by the observed stronger relationships between fall cholera prevalence and available flood affected area (FAA) statistics in Bangladesh (1980–2007) (Akanda et al. 2011). Another important observation from the aforementioned studies is the consistent asymmetric influence of dry- and wet-season processes on same-year spring and fall cholera outbreaks, respectively: negative correlation in spring and positive values in fall. Winter SST in coastal BoB, dry-season rainfall in Bangladesh, and low flow values in GBM rivers all show strong negative influences on spring cholera prevalence; these variables show consistent negative correlation values over subsequent summer and fall seasons, suggesting that freshwater scarcity in upstream rivers and resulting saltwater and plankton intrusion, as well as the environmental changes during the dry season may affect the cholera outbreaks in all the subsequent seasons of the year.

5.22.2.2 Dual-Peak Cholera Dynamics and Impact of Large-Scale Climatic Extremes

The El Niño-Southern Oscillation (ENSO) phenomenon is considered a primary modulator of global climatic events (Ropelewski and Halpert 1986). For example, studies have investigated the relationships between ENSO and streamflow for large tropical rivers such as the Nile and the Congo (Amarasekera et al. 1997; Molinier et al. 2009) and the Ganges (Whitaker et al. 2001). ENSO-related variability has been used to forecast streamflow (Piechota and Dracup 1999; Hamlet and Lettenmaier 1999; Whitaker et al. 2001) and precipitation patterns in the Asian monsoon (Lim and Kim 2007). The ENSO is also known to influence the occurrences of various infectious diseases in many parts of the world (Patz 2002; Harvell et al. 2002). Studies have suggested relationships between the ENSO cycle and cholera epidemics in Peru (Salazar-Lindo et al. 2008; Martinez-Urtaza et al. 2008) and Bangladesh (Koelle et al. 2005; Pascual et al. 2000; Rodo et al. 2002). Studies of large-scale climate effects on infectious disease, including cholera, are limited and have primarily focused on the effects of ENSO in South Asia and Peru (Martinez-Urtaza et al. 2008; Pascual et al. 2000; Rodo et al. 2002).

Extreme climatic events such as prolonged droughts, floods, and major cyclones can cause major cholera and other waterborne epidemics; such extreme events are also likely to create unseen changes in the ecosystem and introduce new biotypes of the harmful pathogens (Siddique et al. 1994, 2010). Studies over the past three decades provided valuable information on the temporal patterns of cholera outbreaks and relationships with ENSO (Rodo et al. 2002; Pascual et al. 2008). However, relationships with cholera and other major diarrheal diseases show limited understanding of the underlying physical processes governing disease transmission.

For example, Pascual et al. (2000, 2008) and Rodo et al. (2002) suggested long-range teleconnections between ENSO and Bengal cholera but did not elaborate on how the warm or cold phase of ENSO would have different impacts on individual seasonal outbreaks. While the Ganges basin part of the region has shown increased flow with the La Niña phase (Whitaker et al. 2001), the higher share of discharge seen in the Brahmaputra Basin has no known influence because of the phenomenon (Jian et al. 2009). As the rivers are known to have a strong contrasting affect on the cholera dynamics in the two outbreak seasons in this region (Akanda et al. 2009), the role of ENSO needs to be interpreted in the context of the seasonal role of individual rivers, not as a teleconnection having a unified affect. Also, Koelle et al. (2005) and Pascual et al. (2008) reported an 11-month lag relationship between ENSO indices and cholera dynamics in Bangladesh; as well as a 14-month lag between rainfall in India and subsequent outbreaks in downstream Bangladesh. However, questions remain on how the warm (El-Niño) and cold (La-Niña) phases of the phenomenon may affect the discharge characteristics of the major rivers in this region differently and how such a large-scale phenomena would affect cholera outbreaks in Bangladesh in two different seasons.

In addition, the occurrences of floods in these rivers have been found to be modulated by separate mechanisms, leading to devastating floods when streamflow peaks coincide (Mirza 2003). Thus, instead of analyzing the ENSO teleconnections as unified influences, the effects on streamflow and precipitation characteristics in each river basin should be investigated separately. In addition to ENSO, long-term records of the global climatic phenomena such as the Indian Ocean Dipole (IOD) (Saji et al., 1999) and Pacific North America (PNA) oscillation (Peings et al., 2009) need to be studied to identify the impacts on the dry- and wet-season hydroclimatologies in the region and the changes in climatic variables relevant to cholera.

Jutla et al. (2010) reports how the coastal environmental and hydroclimatic processes can modulate cholera dynamics in coastal Bangladesh. SST changes in the BoB region can influence the cholera transmission patterns in spring, through changes in the coastal production characteristics (Jutla et al. 2011), and also in fall, through link region's monsoon precipitation characteristics. Akanda et al. (2009) show that the probability of elevated spring cholera outbreaks is the highest in the strongest drought years and the least during the weakest drought years. The probability of a spring cholera outbreak to exceed a certain threshold of incidence rates is always significantly higher in a water scarce year than in a water abundant year. Conversely, the probability of a large cholera outbreak in fall is found to be distinctively higher for high flood years, although the probability in a lower-than-average flood year was indistinguishable from that of an average flood year in the Bengal Delta.

Akanda et al. (2011) showed that the years showing the highest cholera burden all began with low discharge and thus high saline conditions, thus reinforcing the role of coastal processes in spring. In a drought year, if freshwater flow from upstream regions is anomalously lower during the dry season, the resulting increased coastal salinity extent is expected to expose a bigger segment of the population living in the coastal belt to an environment conducive to vibrio growth and subsequently increased risk of cholera transmission in spring. A scenario opposite to the above scenario is a weak drought year, with anomalously high flow in the GBM rivers during the dry season, when we see lower salinity and limited vibrio growth in estuarine areas and subsequently, lower manifestations of spring cholera incidence. For the later parts of the year, anomalously higher monsoon flow leads to flood inundation across the lower Bengal Delta and an elevated risk of cholera infection. Increased levels of local precipitation and lack of flood drainage can further endanger urban population centers located in floodplains across Bangladesh.

5.22.3 Hydroclimatology and Associated Population Vulnerability

5.22.3.1 Hydroclimatic Variability in the Bengal Delta

The frequency and intensity of hydrologic extremes could increase over many areas during the twenty-first century according to the IPCC projections (IPCC, 2011). Such changes in hydrologic extremes and resulting environmental conditions would likely lengthen the transmission seasons of important water borne diseases and alter their geographic range as well as seasonality (Harvell et al. 2002; Colwell 1996). Studies have shown association between extreme rainfall events and outbreaks of waterborne diseases (Hashizume et al. 2008; Cash et al. 2008). Most of these health effects are likely to occur where hydrologic, climatic, and ecological extremes converge with population vulnerability. Extreme climatic events such as prolonged droughts, floods, or cyclones may increase in the GBM region, which may cause major waterborne epidemics and introduce new biotypes of the bacteria (Siddique et al. 1994).

Seasonal cholera transmission cycles (previous section) also need to be viewed in the context of hydroclimatic variability and observed changes in the region. Hydrological observations over past decades indicate that the annual average runoff in some subtropical and lower midlatitude regions have decreased, while there are forecasts of an increase in high latitudes and parts of the tropics in the coming decades (Milly et al. 2005). It is important to understand that the possible effects of such changes on the transmission of waterborne diseases are likely to be distinctly different in dry and wet seasons. For example, the longer and warmer dry seasons in the Ganges basin region of India (Goswami et al. 2006) are likely to lead to increased water scarcity in downstream Bangladesh. In addition, population and economic growth in the region and diversion in upstream areas are likely to affect water availability and ecosystem health downstream. Lower freshwater flow during the dry season and increased salinity in the GBM estuarine region will also impact safe water and sanitation access at local scales, agricultural activities and crop patterns, and also provide a larger area conducive to bacterial growth and proliferation, subsequently affecting public health in coastal areas (Mirza 2011).

On the other hand, monsoon precipitation variability and resulting runoff changes in the Brahmaputra basin region of South Asia will have further impacts on agricultural productivity, causing loss of lives and property, and on water and sanitation, leading to subsequent water-related disease outbreaks. Goswami et al. (2006) found increasing extreme precipitation events in central India, which covers a large part of the Ganges Basin. One possible outcome of these changes will be devastating floods in eastern and northeast India and downstream GBM floodplains. With the current level of greenhouse gas emissions, by 2080, the number of people flooded annually may increase from 13 million to 94 million in South Asia (Milly et al. 2005). More extreme flood events such as in 1988 or 1998 (Mirza 2011) may occur at shorter intervals and lead to rise in cholera outbreaks and frequent and widespread diarrheal epidemics (Siddique et al. 2011) (Figure 3).

Sea level rise and associated salinity intrusion may also disrupt the estuarine ecosystems and increase riverine salinity extent during the dry season up to that of bigger urban centers (Loucks et al. 2010), providing brackish conditions for increased bacterial growth and subsequent cholera transmission in spring months (Akanda et al. 2011). An important observation of the above analysis is that observed and projected hydroclimatic variability and changes will have detrimental impacts on cholera dynamics in the Bengal Delta region; increased water scarcity in the dry season, higher monsoon rainfall runoff during the wet season, as well as sea level rise and resulting ecosystem changes in southern coastlines. However, increased dry-season discharge and shifting streamflow patterns in the Brahmaputra Basin in the form of higher discharge because of possible warming may provide temporary relief to dry-season scarcity, downstream ecosystem requirements, and overall cholera burden in the downstream GBM region, although the long-term future of such changes and runoff availability in the coming decades remain questionable (Kehrwald et al. 2008; Barnett et al. 2005). Accurate estimation of regional climatic variability and resulting hydrologic and environmental changes will create useful actionable knowledge for water management and public health officials in South Asia for planning and preparing effective adaptation strategies and intervention efforts.

5.22.3.2 Population Vulnerability Over Large Geographic Regions

Previous studies focusing on environmental and climatic drivers of diarrheal disease dynamics have not highlighted the spatiotemporal nature of population vulnerability due to the influence of these large-scale drivers. A large segment of the population in Bengal Delta floodplains remains vulnerable to large-scale waterborne disease transmission mechanisms, influenced by estuarine salinity and inland flood inundation variability, that set the ecological and environmental ‘stage’ for diarrheal outbreaks over large geographic regions. Cholera outbreaks are thus understood to be severely underestimated in the southwestern regions because of increased salinity

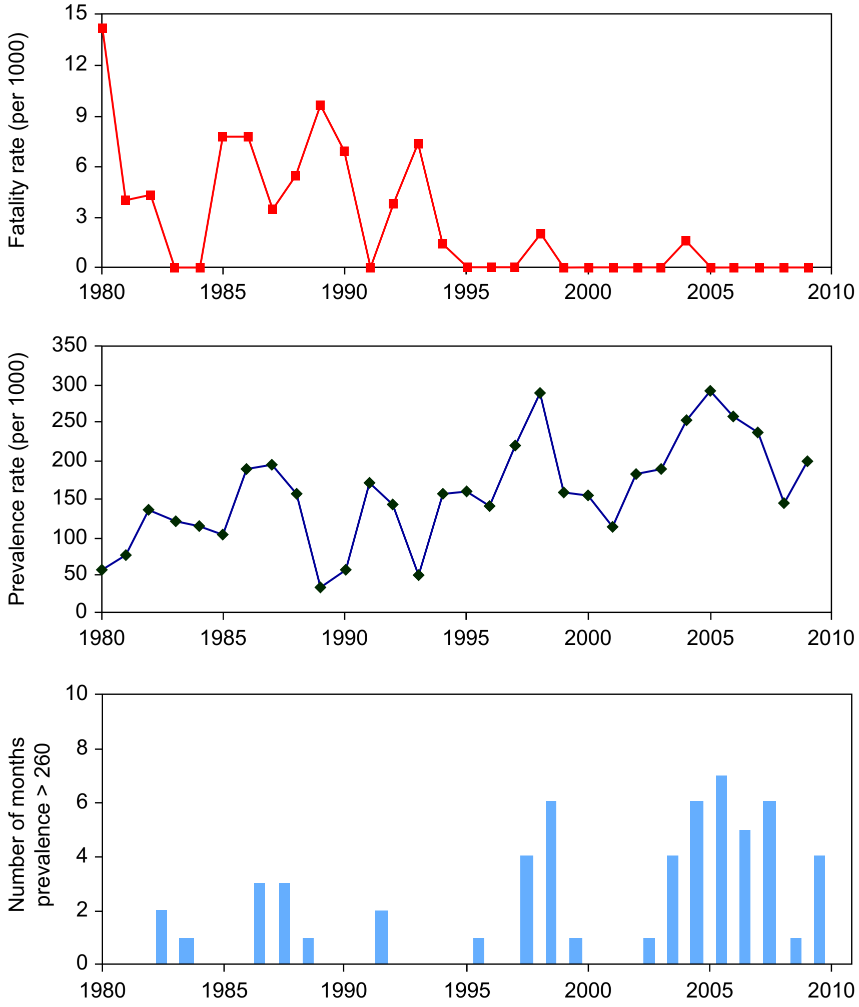

Figure 3 Selected cholera statistics at ICDDR,B (a) Average annual case-fatality ratio in Dhaka (%), (b) average annual prevalence rate for 1980–2009, and (c) number of months with prevalence rate greater than the long-term average 26%.

signatures during spring and because of continuing flood inundation across large areas in fall. An epidemic outbreak in either spring or fall with the concurrent appearance of large-scale climatic extremes such as droughts or floods, respectively, may seriously overburden the public health response system in Bangladesh. A quantitative understanding of the relationships among the hydroclimatological drivers and seasonal diarrheal outbreaks will help early disease detection and prevention efforts. The above linkages can be used to develop 'climate-informed' early warnings and effective means for intervention and preempting epidemic outbreaks in vulnerable regions.

Coastal processes are likely to contribute to spring transmission mechanisms of cholera and other diarrheal diseases, whereas widespread flood inundation and associated physical damage and contamination of water resources seem to dominate disease transmission in fall. To establish the physical role of these seasonal processes in perpetuating the progression of cholera outbreaks from spring to fall, Akanda et al. (2011) performed detailed hydrologic–hydrodynamic simulations over the GBM Basin region in Bangladesh for 20 years (1988–2007) to estimate the nature of salinity intrusion in the dry periods and flood inundation during and after the wet season. Figure 4 shows the spatial distribution of average (MAM: March–April–May months) riverine salinity in southwestern Bangladesh during this period and average flood extent in the wet season (JASO: July–August–September–October months). As seen in Figure 4, population over large geographic sections of Bangladesh remains vulnerable to cholera infection in the spring and fall seasons because of large-scale water contamination and bacterial proliferation in the GBM floodplains in two separate seasonal processes, separately.

In summary, the increased salinity in the estuarine areas during spring provides an optimum environment for growth and increased abundance of *V. cholerae* (Louis et al. 2003; Vital et al. 2007). Inundated lowland areas during and after monsoon floods, on the other hand, provide vast inland areas with standing water and rain-flushed nutrients, providing a growth environment for pathogens (Islam et al. 2006). However, as the above symptoms of transmission mechanisms are typically manifested at a regional scale, other population centers in the floodplains region are also

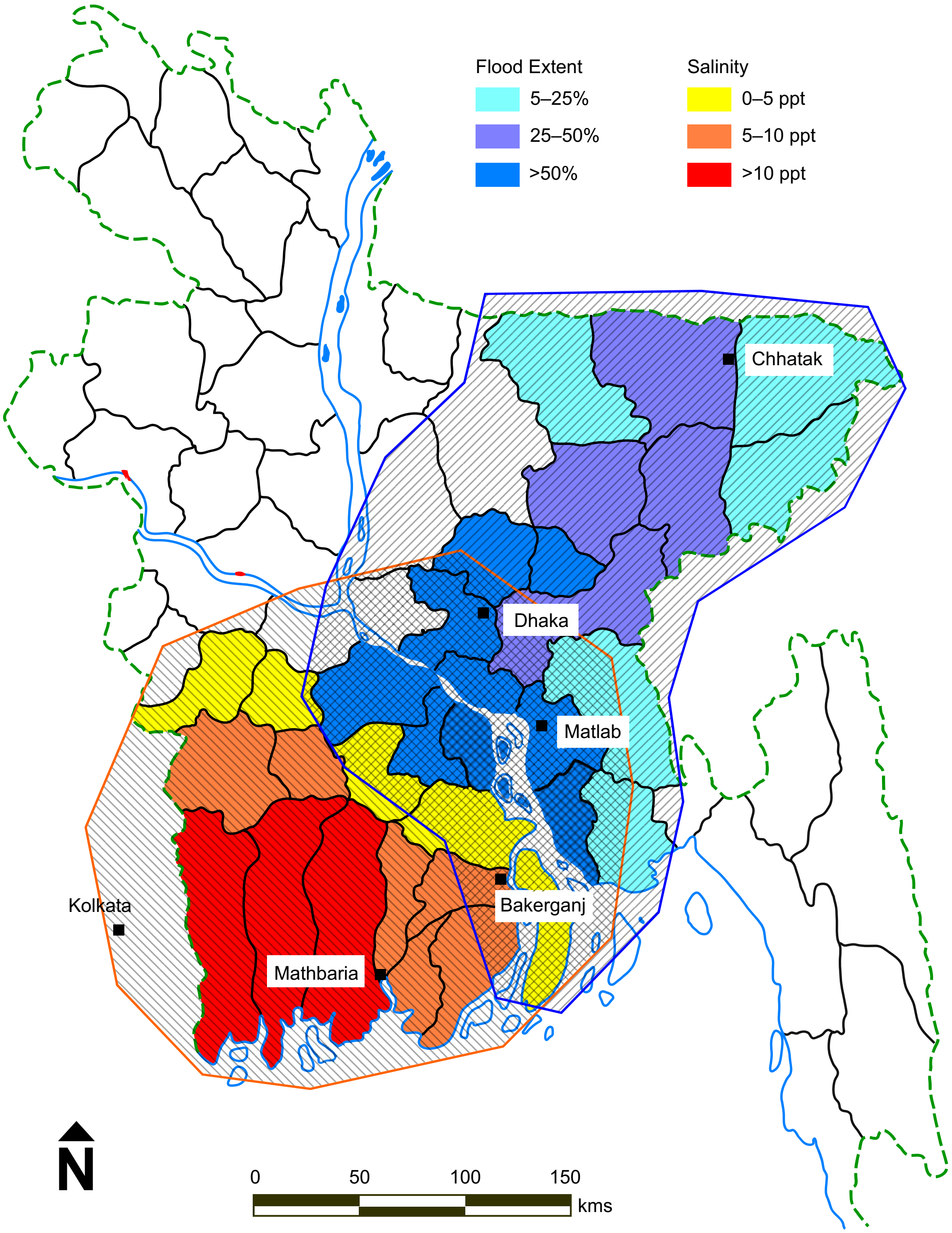

Figure 4 Areas under risk of recurrent cholera outbreaks in spring and fall because of cholera transmission mechanisms driven by coastal salinity intrusion (ppt) (approximate area under influence of the spring transmission mechanism are shown by the orange shaded region) and regional flood inundation (%) (approximate area under influence of the fall transmission mechanism are shown by the blue shaded region) (based on 1988–2007 average).

likely to be vulnerable because of the same mechanisms in the same period. Thus an improved understanding of the macroscale hydroclimatic drivers with accurate estimates of salinity intrusion and flood inundation and their spatial signatures would greatly aid the identification of vulnerable population centers at increased risk of epidemic outbreaks.

5.22.4 Conclusions

5.22.4.1 A Seasonal—Spatial Transmission Paradigm

The combination of a strong seasonal hydroclimatology, high population density, floodplain geography, and coastal ecology has made the Bengal Delta region especially vulnerable to periodic cholera outbreaks. Increasing population and economic development, massive urbanization, and possible changing climate patterns are likely to have significant public health impacts on the region, especially for water-related and waterborne diseases. According to the World Health Organization (WHO) estimates, cholera affects about 3–5 million people annually and about 100,000–150,000 die worldwide each year. The WHO has long supported the development of an early warning system for epidemic cholera outbreaks using climatic and environmental data. Although researchers (Hashizume et al. 2011; Pascual et al. 2008; de Magny et al. 2008) have attempted to predict epidemic cholera outbreaks, an accurate climate-based early warning system is yet to be developed and implemented at an operational level. More importantly, these studies did not sufficiently identify and incorporate the asymmetric and large-scale nature of climatic and environmental influences. The recent findings identify two plausibly important physical variables in the transmission process, estuarine salinity and inland flood inundation, and suggest that seasonal asymmetry and spatial heterogeneity of underlying hydroclimatic processes should be taken into account for developing meaningful predictive models and understanding the scale of population vulnerability to disease transmission mechanisms over large geographic regions.

In this study, we provide a physical understanding based on the regional large-scale environmental and hydroclimatic processes on how the first outbreaks of cholera may be related to low flow discharge of the GBM rivers and subsequent plankton intrusion during spring. Cholera incidence values in this season are inversely related to streamflow volumes, that is, bigger spring cholera peaks are seen in strong drought years. On the other hand, autumn cholera outbreaks are positively correlated to peak streamflow volumes, that is, bigger autumn peaks are seen in high flood years. Evidence points to the breakdown of sanitation and subsequent water contamination, which impacts the population gathered in the few remaining dry areas.

Lack of reliable and continuous cholera incidence data as well as poor coverage in both time and space has traditionally hindered research on understanding the climate–cholera connection. Most published literature on Bengal cholera and climate have only used data from Matlab (e.g., Pascual et al. 2008; Koelle et al. 2005; Cash et al. 2008; Islam et al. 2009), a small coastal town in Bangladesh, and consequently, provided a potentially skewed and incomplete understanding of transmission and propagation of cholera in the Bengal Delta region.

Recent findings indicate that *V. cholerae* outbreaks can be highly local, occurring simultaneously in various locations possessing favorable environmental conditions (Stine et al. 2008; Alam et al. 2011). Thus, the likelihood of an epidemic cholera outbreak in Dhaka because of an extreme hydroclimatic event, such as a drought or a flood, means that major population centers along the floodplains are also concurrently vulnerable (Akanda et al. 2011). The results also suggest that with such an understanding of the underlying large-scale drivers, there is potential to predict the timing and magnitude of cholera outbreaks.

The presented analyses indicate that estuarine salinity and inland flood inundation can significantly affect cholera transmission in the Bengal Delta region. In addition, our analyses show that large areas of the highly populated floodplains in this region remain at high risk of epidemic outbreaks in spring and fall because of the large spatial coverage of salinity intrusion and flood inundation, respectively. Population centers along the floodplain corridors of the GBM river system such as Dhaka and Matlab remain vulnerable to such cholera transmission mechanisms in both the spring and fall seasons (Figure 4). The physical basis of this argument is that the highly asymmetric hydrology of the GBM region leads to a drastic reduction of streamflow from upstream regions in the dry season and a significant drop in the hydraulic head, accelerating the salinity intrusion from BoB toward inland freshwater (Rahman et al. 2000). This inward movement of seawater may help transport *V. cholerae* from coastal areas, and the increased salinity of the estuarine rivers also provides a larger optimal growth environment for the bacterium.

Another important finding of this study is that GBM cholera outbreaks are propagated from the spring to fall seasons and from the coastal to inland regions because of the physical nature of underlying hydroclimatic drivers. Schwartz et al. (2006) reported that *V. cholerae* strains isolated during peak monsoon months are identical to the strains detected in subsequent fall outbreaks, and this strengthens the hypothesis of a second transmission cycle beginning in summer and continuing into fall. Future research needs to focus on a detailed characterization of estuarine salinity at a community scale, which will be helpful for early identification of population vulnerability and targeted intervention and mitigation of spring outbreaks. Also, maintaining higher dry-season discharge in specific rivers (e.g., through the Gorai, the main distributary of the Ganges into southwestern Bangladesh) may have significant beneficial impacts on public health in later seasons of the year.

5.22.4.2 Policy and Public Health Implications

The previous sections of this chapter discussed how cholera outbreaks in the Bengal Delta region were linked to and modulated by significant hydroclimatic events during the past three decades. The findings can be incorporated into a predictive surveillance capability that would help identify vulnerable population groups in the region at risk of imminent cholera outbreaks depending on salinity or flooding signatures in coastal and inland regions as measured 2–3 months in advance. Such a capability would help save lives not only in the urban settings of Dhaka but also in rural population centers along the floodplains of the major rivers that are affected by the large-scale seasonal and spatial large-scale drivers. A predictive system based on the specific information of salinity intrusion and flood inundation patterns shows the promise of predicting future intensity of disease transmission in coastal and inland areas, respectively, and plausibly provides the public health authorities the specific warning necessary to alert medical personnel and implementing preventive measures ahead of epidemic outbreaks.

Recent findings on the large-scale controls of seasonal cholera dynamics suggest that detailed spatial hydroclimatic and hydrodynamic modeling can provide a much-needed lead time to predict the magnitude and location of cholera outbreaks from weeks up to a few months in advance. Seasonal streamflow patterns, coastal plankton abundance, as well as salinity intrusion and flood inundation signatures can be skillful predictors of cholera incidence for the Bengal Delta region and Sub-Saharan Africa. A macrolevel understanding of diarrheal transmission mechanisms is especially vital in the face of observed changes in weather patterns in many developing countries that are vulnerable to endemic and epidemic cholera outbreaks. Based on the accurate prediction and estimated risk of cholera outbreaks, early warnings can be issued in mass media and propagated through cellular-phone-based networks in remote areas. Such networks have proved extremely successful in coastal areas of Bangladesh in reducing cyclone fatality recently and have great potential to be used for epidemic warnings and in adaptation strategies focusing on climate impacts of public health (Akanda et al. 2012).

Evidence suggests that a well-implemented water, sanitation, and hygiene (WASH) infrastructure can significantly reduce diarrheal disease prevalence (Bartram and Cairncross 2010). Such improvements usually require considerable time and resources; however, targeted implementation of WASH in vulnerable localities is feasible and has been highly effective. Large-scale changes in freshwater availability and distribution can severely affect water and sanitation access and public health at the local scale (Howard et al. 2010) and subsequently affect the ability to reach the Millennium Development Goals for most developing countries (Veneman, 2006). A large-scale approach of understanding diarrheal disease mechanisms can also help public health officials make WASH projects more efficient based on early warnings and administer targeted intervention in vulnerable regions. Cholera disease burden can be reduced by predicting impending outbreaks with an actionable lead time of a month to several months and mobilizing experts (physicians and public health workers) and material resources (water purification and sanitation equipment, vaccines, and ORS) to target areas (Akanda et al. 2012).

A climate-based understanding and knowledge of environmental and hydroclimatic drivers can provide a critical time window ahead of impending epidemic cholera outbreaks and enhance the efficacy of existing intervention methods. The combined impact of the proactive and preventive intervention strategies would help reduce the enormous disease burden in the developing world. The role of large-scale hydroclimatic variability in water-related disease transmission is thus a critical component of the climate-water-health nexus and should be incorporated into climate mitigation and adaptation strategies geared toward public health.

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5.23 Flood Inundation and Crop Damage Mapping: A Method for Modeling the Impact on Rural Income and Migration in Humid Deltas

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5.23.1 Introduction

The humid tropics are generally resource-rich lands. They possess adequate water supply, naturally fertile soils, and a favorable terrain. The morphology of these areas ranges from flat lowland delta to river valleys associated with gently rolling uplands. Most of the major deltas in the world (e.g., Ganges, Mississippi, Niger, Okavango, and Mekong deltas) host large population centers, megacities, complex irrigation systems, and a water-sensitive ecosystem because of their easy access to abundant fresh water and fertile soils. Humid deltas of developing nations support extensive agricultural production. Flooding (extreme and normal) is recurrent in these humid deltas. Floods promote as well as hamper agricultural productivity (depending on the magnitude and spatial extent). Therefore, the socioeconomic fabric of the rural areas of humid deltas in developing nations is intricately related to recurrent flooding, agricultural productivity, and crop loss pattern.

Qualitatively it is easily understood that above-average flooding in these areas may potentially initiate a three-step chain reaction with socioeconomic implications as follows: step (1) floods damage crops; step (2) crop damage results in income loss (seasonal loss of income for farmers); step (3) income loss results in migration (generally toward urban areas). Understanding this three-step chain reaction by quantitative approximation is very important to understanding the observed space–time trends in temporary migration and loss of income for farmers due to recurrent flooding in humid deltas, especially from a climate perspective.

Traditional climate adaptation strategy is usually based on Intergovernmental Panel on Climate Change (IPCC) types of projections (available for various emission scenarios), which is usually predicted by the atmospheric–ocean general circulation models (GCMs) at relatively coarser resolution (Solomon et al. 2007). The adaptation strategy uses the IPCC scenarios without incorporating nonlinearities and interdependencies among resources following a top-down approach and thereby involves uncertainties and could be very risky to adapt (e.g., MoEF 2008). Researchers also increasingly recognize the challenge of skillful forecasts of future global and regional climate due to the diverse types of global and regional radiative and nonradiative climate forcings (Pielke 2001). None of the existing global climate models include all of the important forcings and feedbacks (Pielke et al. 2004). Kabat et al. (2004) proposed a new vulnerability paradigm to address the limitations of using global model projections as the primary basis to determine the potential impacts of future climate variations. This vulnerability paradigm, as applied to the Earth system, is a more inclusive approach than prediction. Key vulnerabilities include risks, for example, to regional and global food, water, and energy supplies (Pielke et al. 2004). Sarewitz et al. (2000) suggested that an approach of first assessing key societal and environmental vulnerabilities and then seeking to determine if skillful predictions are possible can accommodate the uncertainties involved in GCM-based, top-down climate adaptation strategies. According to Pielke et al. (2004) and Pielke et al. (2011), the framework for vulnerability assessments should be place-based and have a bottom-up perspective, in contrast to the GCM-focused top-down approach from a global perspective. The vulnerability focus should be on the resource of interest. This chapter addresses the determination of space–time trends in temporary migration and loss of income for farmers due to recurrent flooding from a bottom-up assessment approach. Such an approach can greatly benefit the climate vulnerability assessment and adaptation strategy for humid deltas in developing nations because of its highly contextual nature.

Satellite remote sensing has been used to study crop patterns (e.g., Moran et al. 1997), estimating crop damage (e.g., Okamoto et al. 1998; Silleos et al. 2002) and detection of flood inundation extent (e.g., Smith 1997; Horritt et al. 2001;

http://dx.doi.org/10.1016/B978-0-12-384703-4.00536-0

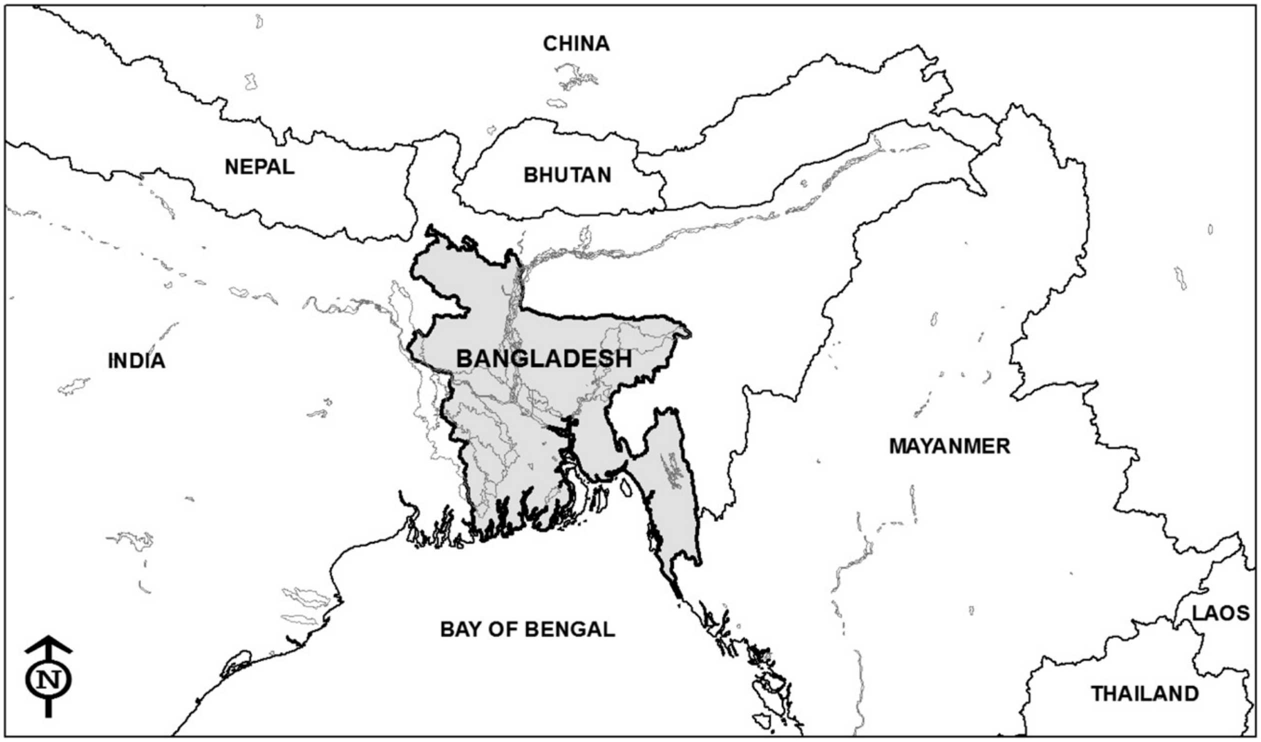


Figure 1 Regional setup of Ganges–Brahmaputra delta (Bangladesh).

Henry et al. 2006) for many years. Hydrologic remote sensing from satellite platforms (NASA products on precipitation, water extent, and water level) also has a proven track record of use for transboundary flow forecasting/prediction. Therefore, because of easy availability and the vantage of space offering a more comprehensive view of a region, satellite data naturally lends itself to routine and affordable monitoring of flooding and crop damage for policy planners at the administrative level. However, no comprehensive research has been conducted to investigate: (1) if satellite remote-sensing data that is used for detection of flooding and crop damage patterns is a reliable and routine proxy for use in socioeconomic models to assess loss of income and migration patterns; and (2) if it is found that remote sensing is reliable as a proxy for migration patterns at planning timescales, what is the 'tipping point' crop damage extent that causes disruptive environmental–economic migration? This chapter provides a summary of the state of the art of remotely sensed data and digital image processing techniques for the successful completion of such a comprehensive research.

This chapter briefly presents the climate vulnerability scenarios of Bangladesh by the bottom-up approach; discusses potential methods and techniques to study the observed space–time trends in temporary migration and loss of income for farmers due to recurrent flooding in humid deltas as a case study in Bangladesh; and reports the existing knowledge base to support each component of the potential methods and techniques described in the first section. The chapter also reports the gaps in the existing knowledge base and recommends potential scope of research to support the remote-sensing-based migration study.

5.23.2 Case Study Site: Bangladesh

Bangladesh (Ganges–Brahmaputra Delta in general—Figure 1) is a representative example of most humid, flood-prone, and heavily populated deltas of Asia and Africa. The availability of much insitu hydrologic data, calibrated models on hydrology and hydraulics, benchmarking of several National Aeronautics and Space Administration (NASA) products and systems, agreements with local agencies, and familiarity with the region are the major factors that influence the decision of the site selection.

Bangladesh is located between 20°and 26° N latitude and 88° and 92° E longitude. It is bordered by India on the west, north, and east; by Myanmar on the southeast, and by the Bay of Bengal on the south. Most of the country is characterized by low-lying land comprising mainly the delta of the Ganges and Brahmaputra rivers. Floodplains occupy about 80% of the country. The mean elevations range from less than 1 m on tidal floodplains; 1–3 m on the main river and estuarine floodplains; and up to 6 m in the northeast (Rashid 1991). Only in the extreme northwest are elevations greater than 30 m above the mean sea level. The hilly areas are occupied in the northeast and southeast portions of the country, with some tertiary hills over 1000 m above mean sea level.

In general, Bangladesh is characterized by a humid, warm, and tropical climate. The climate is influenced primarily by monsoons and partly by pre- and postmonsoon circulations, which mostly originate over the Indian Ocean and carry warm, moist, and unstable air. The onset of the monsoon starts during the first week of June and ends in the first week of October (with some interannual variability in dates). In addition to monsoons, the easterly trade winds are also active in this area, providing warm and relatively drier circulation. There are four prominent seasons in Bangladesh: (1) winter (Dec. to Feb.), (2) premonsoon (Mar. to May), (3) monsoon (Jun. to early Oct.), and (4) postmonsoon (late Oct. to Nov.). Agrawala et al. (2003) described the general characteristics of the seasons in Bangladesh as follows:

1. Winter is relatively cooler and drier. The average temperature range from a minimum of 7.2–12.8 °C to a maximum of 23.9–31.1 °C. The minimum occasionally falls below 5 °C in the north. There is a south to north thermal gradient in winter mean temperature, and generally the southern districts are 5 °C warmer than the northern districts. Frost or snowfall is extremely rare.
2. Premonsoon is hot with an average maximum temperature of 36.7 °C, predominantly in the west for up to 10 days, very high rate of evaporation, and erratic but occasional heavy rainfall from Mar. to Jun. In some places, the temperature occasionally rises up to 40.6 °C or more. The peak of the maximum temperatures is observed in April, the beginning of premonsoon season. In the premonsoon season, the mean temperature gradient is oriented in a southwest to northeast direction, with the warmer zone in the southwest and the cooler zone in the northeast.
3. Monsoon is both hot and humid, and brings heavy torrential rainfall throughout the season. About four-fifth of the mean annual rainfall occurs during monsoon. The mean monsoon temperatures are higher in the western districts compared to those for the eastern districts. Warm conditions generally prevail throughout the season, although cooler days are also observed during and following heavy downpours.
4. Postmonsoon is a short season characterized by withdrawal of rainfall and gradual lowering of nighttime minimum temperatures.

The annual rainfall in Bangladesh ranges from 1200 mm in the extreme west to over 5000 mm in the east and northeast, with a mean annual rainfall of about 2300 mm.

Bangladesh, with an estimated population of about 151.41 million and a population density of about 964 persons per km^2 (BBS 2011) is one of the most populous and densely populated countries in the world (World Bank 2010). The country gained a net population increase of more than 114 million from 1901 to 2011 (BBS 2011). As in some other developing countries, in Bangladesh, the rate of urbanization is extremely high (more than two to three times that of the national population growth rate), being consistently over 5% since 1961, and even up to 20% in some years (Jahan and Rouf 2011) (Table 1). In 1974 people living in urban areas accounted for only 8.8% of the total population. In 2001 the urban population became 23.10% of the total population. The United Nations (UN) estimates that currently about 25% of the people of Bangladesh live in urban areas (Jahan and Rouf 2011).

Migration contributed about 40% to the urban growth in Bangladesh during 1974–81 (Islam 1999). The share was probably similar during 1981–91. For some large cities, this share could even be higher—up to 70%—as in the case of the capital city of Dhaka. The variable contribution of migration to urban growth by cities is evident from Table 2. On the aggregate level, both in- and out-migrations have increased in Bangladesh consistently since 1984 (BBS 1994; Huq-Hussain 1995). The increase is significantly higher in the case of in-migration than of out-migration, indicating robust net migration trends (Figure 2(a)–2(c)).

Table 1 Level of urbanization in Bangladesh (1941–2001)

Census year	*Total national population*	*Total urban population*	*Level of urbanization (%)*
1941	41 997 297.00	1 537 244.00	3.66
1951	42 062 610.00	1 819 773.00	4.33
1961	50 840 235.00	2 640 726.00	5.19
1974	71 479 071.00	6 273 602.00	8.78
1981	87 120 119.00	13 535 963.00	15.54
1991	111 455 185.00	22 455 174.00	20.15
2001	123 851 120.00	28 605 200.00	23.1

Adapted from Jahan, S., and M. A. Rouf, 2011: *Growth of Urbanization and Urban Centers in Bangladesh, Urban Feature of Bangladesh: Making Cities and Towns Work for All*, A Special Publication, Bangladesh Urban Forum, Dhaka, December 5–7, 10–17.

Table 2 Components of population growth in four major cities in Bangladesh, 1961–2011

	Population (thousands)			
City name	*1961*	*2006*	*2007*	*2008 (estimated)*
Dhaka	521	6475	6733	7001
Chittagong	364	2438	2532	2579
Khulna	175	830	843	856
Rajshahi	57	447	460	473

Adapted from Khan, A. A. M., 1982: Rural urban migration and urbanization in Bangladesh. *Geogr. Rev.*, **72** (4), 79–94.

Dhaka is the largest city in Bangladesh and also the financial, business, and cultural center of the country. The area and population of Dhaka city grew about 58-fold and 35-fold, respectively. Dhaka is also the fastest growing megacity in the world along with Lagos, Nigeria. Dhaka's share of the country's total population has been steadily growing, with a current rate of over 10%. According to UN and World Urbanization Prospects (2009) projection, Dhaka is to move up to the position of fifth-largest megacity with an estimated population of 20.9 million in 2025.

A time series of Landsat-3 Multispectral Scanner System (MSS), Landsat-4/5 Thermatic Mapper (TM), and Landsat-7 Enhanced Thermal Mapper Plus (ETM+) data acquired over Dhaka city were obtained from NASA and the US Geological Survey (USGS) and processed to visually inspect the evidence of high-intensity urban development in Dhaka. Table 3 shows the dates of the acquired Landsat imagery.

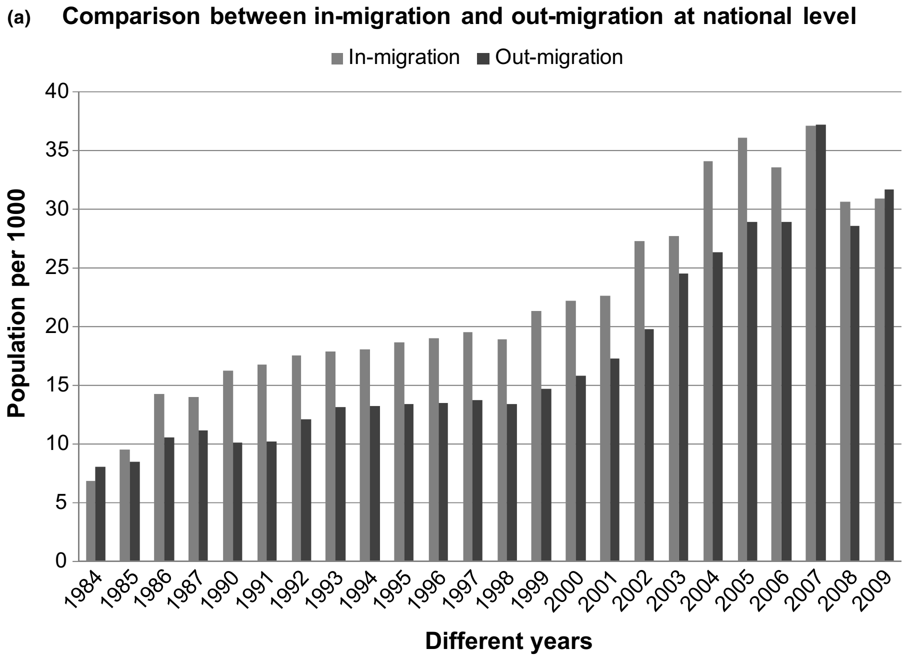
The images were processed, georectified, and displayed with administrative vector layers. The images were displayed as false color composite to emphasize the contrast among vegetation, water, and urban developments. The MSS images were displayed by 1 (red), 3 (green), and 2 (blue) band combinations. The TM and ETM+ images were displayed by 3 (red), 4 (green), and 2 (blue) band combinations. In all cases, vegetated areas are represented by green, and urban areas (mostly impervious surfaces) are represented by light purple. Rivers and other water bodies are represented by black, dark blue, and dark purple colors. Figure 3 shows Dhaka city as captured by the Landsat satellites in 1980, 1989, 2000, and 2003. Figure 4 shows

Dhaka city as captured by the Landsat satellites in 2005, 2006, 2009, and 2010. The time series of these satellite observations clearly shows the major episodes of urban developments in and around Dhaka city.

Most of Dhaka's growth is due to migration from rural areas, especially from the neighboring districts (Figure 5). Due to a disproportionately large concentration of administrative, industrial, educational, and cultural activities, Dhaka city is not only the permanent destination of rural migrants but also attracts hundreds and thousands of daily commuters and circular migrants from neighboring rural districts (Islam 1996).

5.23.3 Climate-Vulnerability Scenarios of Bangladesh by Bottom-Up Approach

Bangladesh is one of the most populous and densely populated countries in the world. It is also one of the poorest countries in



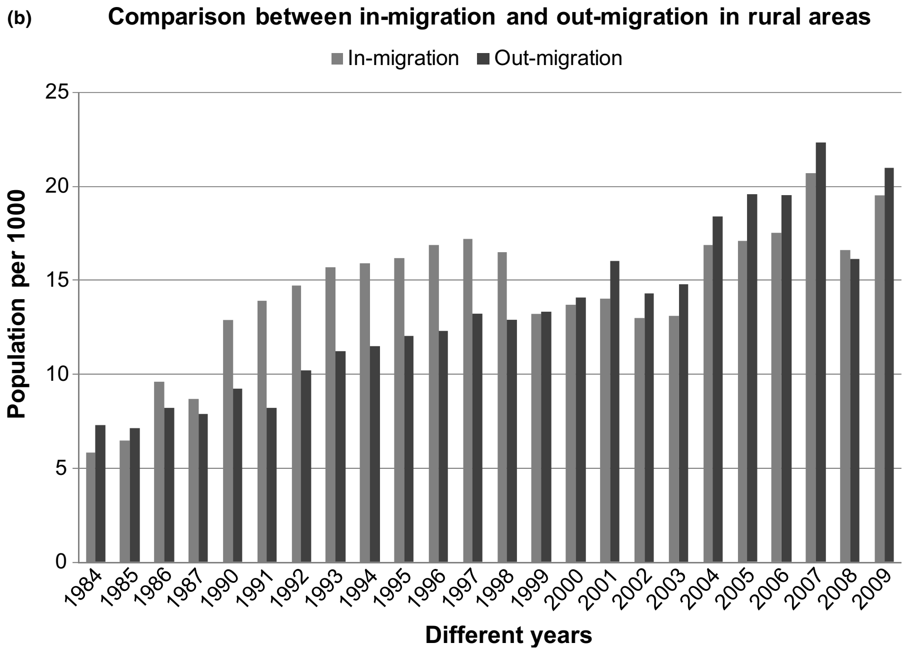


Figure 2 (a) Comparison between in-migration and out-migration rates (1984–2009) at national level. (b) Comparison between in-migration and out-migration rates (1984–2009) in rural areas. (c) Comparison between in-migration and out-migration rates (1984–2009) in urban areas. Adapted from Huq-Hussain, S., 1995: Pattern of internal migration in Bangladesh: Some new dimensions in female migration. *Orient. Geogr.*, **39** (1–2), 86–105 and BBS (Bangladesh Bureau of Statistics), 1994: *Bangladesh Population Census, Report on Sample Vital Registration in Bangladesh 1981–1992*. Government of Bangladesh, Dhaka.

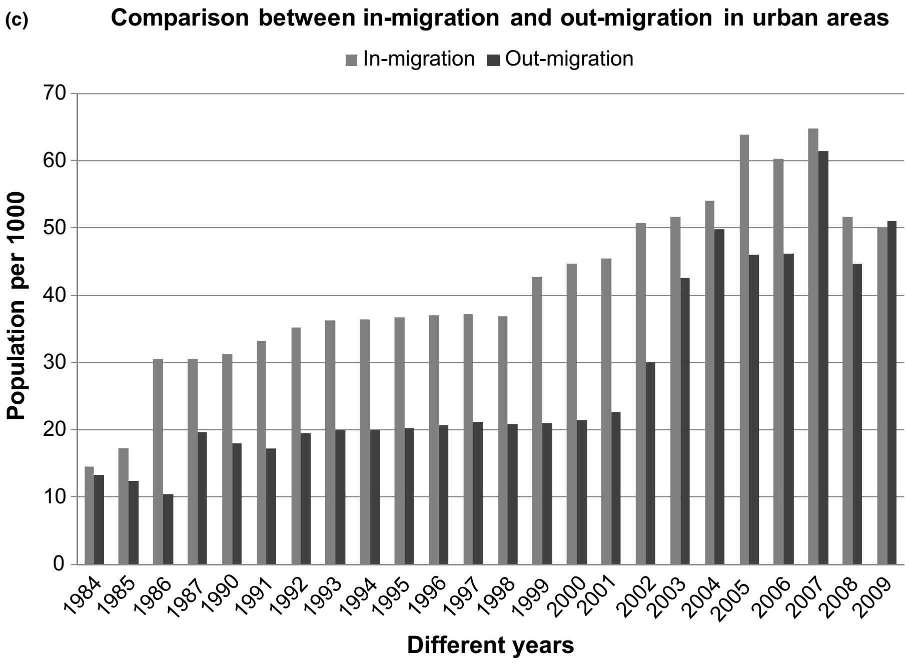


Figure 2 (*Continued*).

Table 3 List of Landsat imagery obtained from NASA

Mission	*Sensor*	*Data acquisition dates*
Landsat-3	MSS	Feb. 20, 1980
Landsat-4	TM	Jan. 28, 1989
Landsat-7	ETM+	Feb. 28, 2000
Landsat-7	ETM+	Mar. 24, 2003
Landsat-5	TM	Jan. 16, 2005
Landsat-5	TM	Nov. 3, 2006
Landsat-5	TM	Jan. 11, 2009
Landsat-5	TM	Feb. 15, 2010

the world with a per capita income of $640, which ranks below average South Asian per capita income and per capita income for low-income countries (World Bank 2010). More than one-third (36%) of the people in Bangladesh live in poverty (in rural areas, it is 40%). With the burden of tremendous population growth problem, Bangladesh ranks low on just about all measures of economic development. This low level of development makes the country quite vulnerable to climate, as it combines with a number of hydrogeological and socioeconomic factors such as (1) geographical location in South Asia; (2) flat deltaic topography with very low elevation; (3) extreme climate variability that is governed by monsoon patterns (which results in acute water distribution over space and time); (4) high population density and poverty incidence; and (5) majority of population being dependent on agriculture (about one-quarter of the country's GDP comes from it) (Ahmed 2006).

Although it is difficult to determine Bangladesh's potential to adapt to climate, several key statistics give some insight as to the state of its infrastructure and its social and human capital. In 2000, the World Bank estimated that only 9.5% of the total network (207 500 km) of roads in Bangladesh was paved, which put it well below the average (16.5%) for low-income countries (World Bank 2002), suggesting that its physical infrastructure in general might be less developed than that of low-income countries. In the same year, the World Bank also reported that Bangladesh had only 51 scientists and engineers per million people, a number comparable to that for low-income countries in general. Similarly, gross secondary and tertiary school enrollment stood at 47.5% and 4.8%, respectively, in 2000. A relatively uneducated and illiterate population will be less capable of adapting to climate variations and thus has higher vulnerability.

Several studies, including Agrawala et al. (2003), World Bank (2000), and Huq et al. (1999), discussed the potential impacts of climate on water resources in Bangladesh. Water-related impacts of climate will likely be the most critical for Bangladesh, largely related to coastal and riverine flooding (Agrawala et al. 2003).

Flooding in Bangladesh is a regular feature and has numerous adverse effects, including loss of life, increased frequency of disease, and destruction of property. This is because (1) there are 230 rivers that occupy about 7% of the total land area of Bangladesh, and (2) much of the country is located on a floodplain of three major rivers and their numerous tributaries. The combined basin area of these great river systems is about 1.72 million km^2 and spread over China, India, Nepal, Bhutan, and Bangladesh (Figure 1). Bangladesh is the lowest riparian country with low topography in the basin, and these three major rivers discharge into the Bay of Bengal through the heart of Bangladesh. One-fifth of the country is flooded every year, and in extreme years, two-thirds of the country can be inundated (Mirza 2002). This vulnerability to flooding is exacerbated by the fact that Bangladesh is also

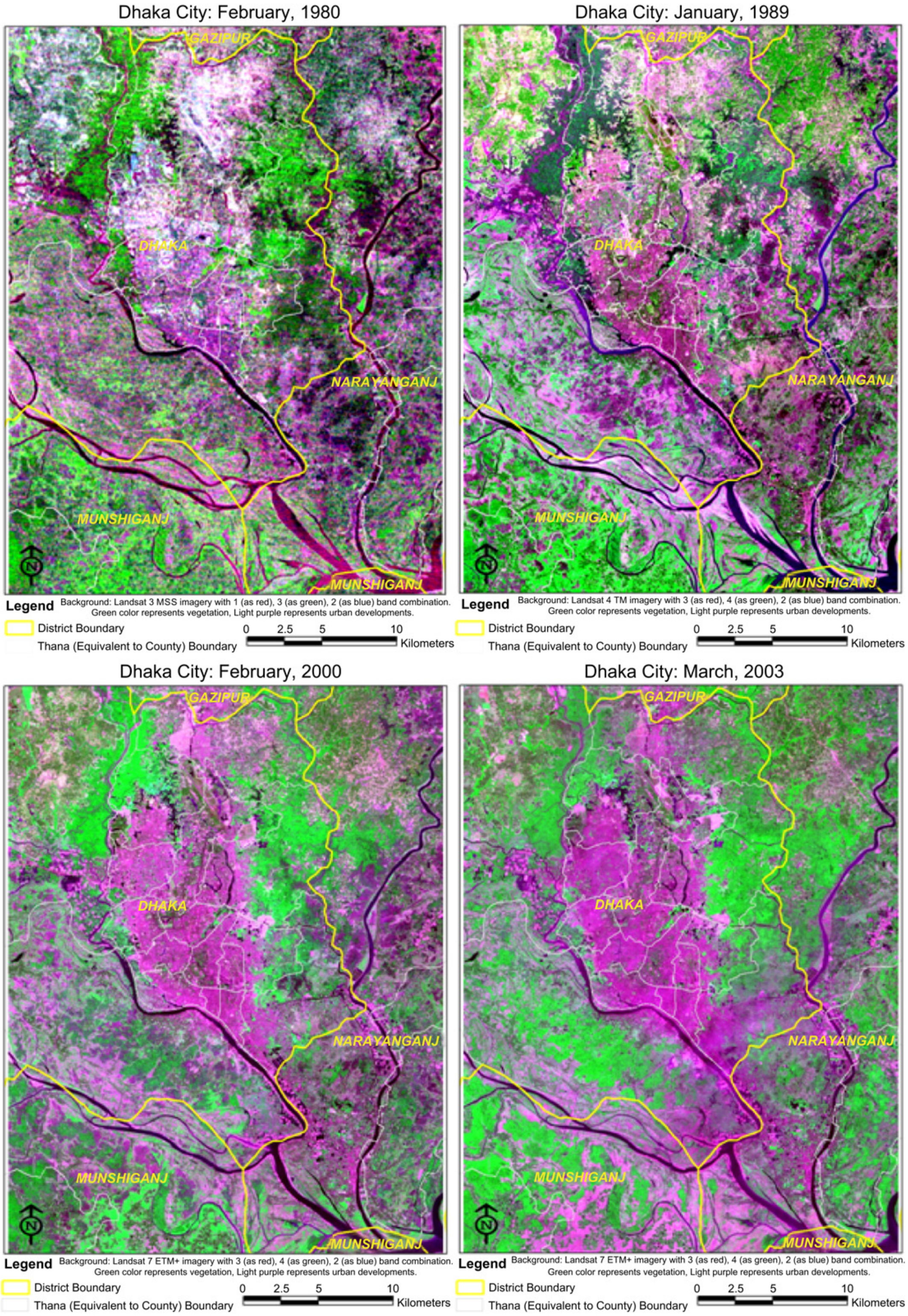
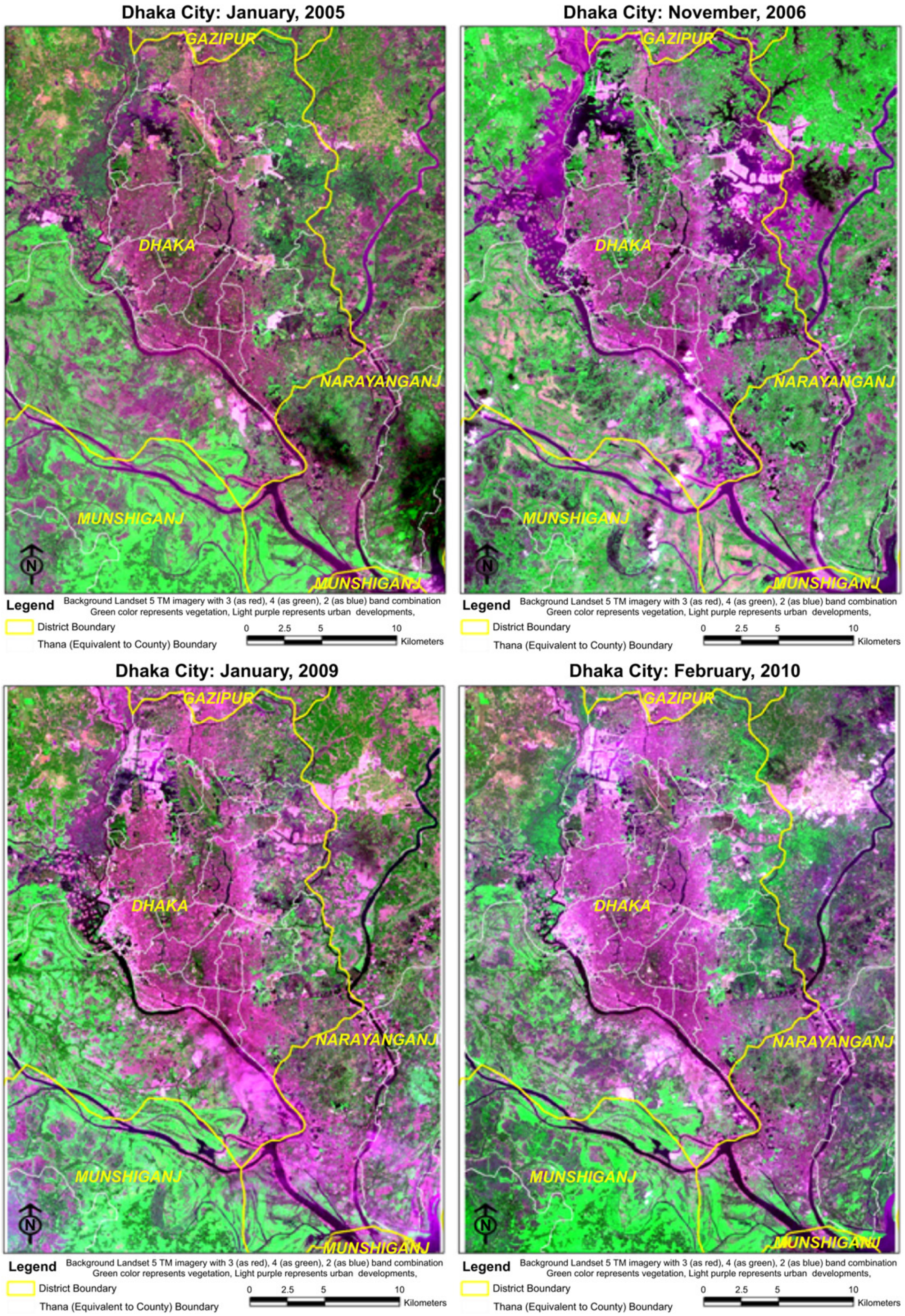

Dhaka City: February, 1980
GAZIPUR
DHAKA
NARAYANGANJ
MUNSHIGANJ
MUNSHIGANJ
N
Legend
Background: Landsat 3 MSS imagery with 1 (as red), 3 (as green), 2 (as blue) band combination.
Green color represents vegetation, Light purple represents urban developments.
District Boundary
Thana (Equivalent to County) Boundary
0 2.5 5 10
Kilometers
Dhaka City: January, 1989
GAZIPUR
DHAKA
NARAYANGANJ
MUNSHIGANJ
MUNSHIGANJ
N
Legend
Background: Landsat 4 TM imagery with 3 (as red), 4 (as green), 2 (as blue) band combination.
Green color represents vegetation, Light purple represents urban developments.
District Boundary
Thana (Equivalent to County) Boundary
0 2.5 5 10
Kilometers
Dhaka City: February, 2000
GAZIPUR
DHAKA
NARAYANGANJ
MUNSHIGANJ
MUNSHIGANJ
N
Legend
Background: Landsat 7 ETM+ imagery with 3 (as red), 4 (as green), 2 (as blue) band combination.
Green color represents vegetation, Light purple represents urban developments.
District Boundary
Thana (Equivalent to County) Boundary
0 2.5 5 10
Kilometers
Dhaka City: March, 2003
GAZIPUR
DHAKA
NARAYANGANJ
MUNSHIGANJ
MUNSHIGANJ
N
Legend
Background: Landsat 7 ETM+ imagery with 3 (as red), 4 (as green), 2 (as blue) band combination.
Green color represents vegetation, Light purple represents urban developments.
District Boundary
Thana (Equivalent to County) Boundary
0 2.5 5 10
Kilometers

Figure 3 Dhaka city as observed by Landsat satellites from 1980 to 2003. Green represents vegetated areas and light purple represents urban development.



Dhaka City: January, 2005

Dhaka City: November, 2006

Dhaka City: January, 2009

Dhaka City: February, 2010

GAZIPUR
DHAKA
NARAYANGANJ
MUNSHIGANJ
MUNSHIGANJ
N
Legend
Background Landset 5 TM imagery with 3 (as red), 4 (as green), 2 (as blue) band combination
Green color represents vegetation, Light purple represents urban developments,
District Boundary
Thana (Equivalent to County) Boundary
0 2.5 5 10
Kilometers

Figure 4 Dhaka city as observed by Landsat satellites from 1980 to 2003. Green represents vegetated areas and light purple represents urban development.

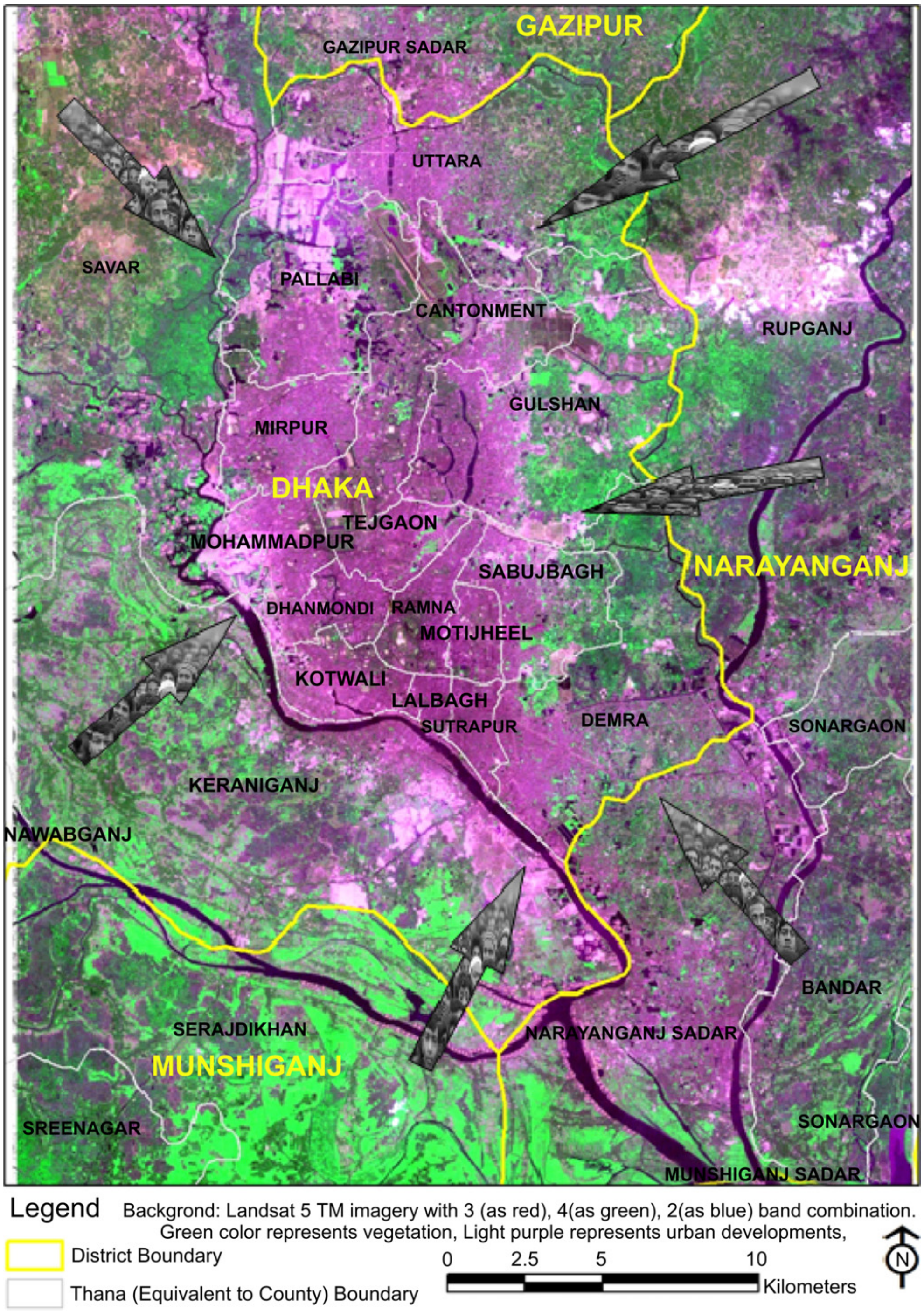

GAZIPUR
GAZIPUR SADAR
UTTARA
SAVAR
PALLABI
CANTONMENT
RUPGANJ
GULSHAN
MIRPUR
DHAKA
TEJGAON
MOHAMMADPUR
SABUJBAGH
NARAYANGANJ
DHANMONDI
RAMNA
MOTIJHEEL
KOTWALI
LALBAGH
SUTRAPUR
DEMRA
SONARGAON
KERANIGANJ
NAWABGANJ
BANDAR
SERAJDIKHAN
NARAYANGANJ SADAR
MUNSHIGANJ
SREENAGAR
SONARGAON
MUNSHIGANJ SADAR
Legend
Backgrond: Landsat 5 TM imagery with 3 (as red), 4(as green), 2(as blue) band combination.
Green color represents vegetation, Light purple represents urban developments,
District Boundary
Thana (Equivalent to County) Boundary
0 2.5 5 10
Kilometers
N

Figure 5 Urban development in Dhaka city due to migration from surrounding districts.

a low-lying deltaic nation exposed to storm surges from the Bay of Bengal.

Severe floods occurred in 1954, 1955, 1970, 1974, 1984, 1987, 1988, 1998, 2004, and 2007. Severe coastal flooding occurred in the years 1822, 1876, 1897, 1942, 1950, 1970, 1974, 1988, 1991, 1994, 1995, and 2007. Based on the historic records, it appears that the frequency, magnitude, and duration of floods have increased substantially during the past few decades. For example, all major floods covering more than 35% of the country occurred after 1974 (Figure 6).

The 1998 flood, one of the worst in recent memory, is an example of how vulnerable Bangladesh is to flooding. The flood was the result of three factors: (1) heavy rainfall and snowmelt in India and Nepal, (2) a 20% increase in rainfall in Bangladesh into its major rivers (the Ganges and

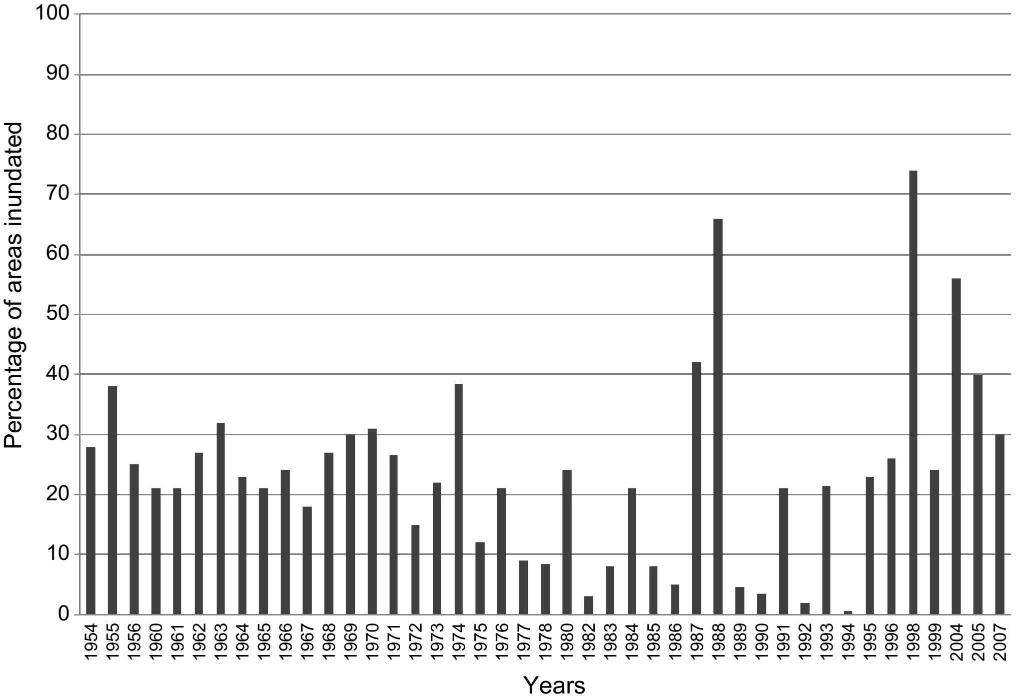


Figure 6 Comparison of flooded areas for different years in Bangladesh. Adapted from Agrawala, S., T. Ota, A. U. Ahmed, J. Smith, and M. Aalst, 2003: *Development and Climate Change in Bangladesh: Focus on Coastal Flooding and the Sunderbans*. Organization for Economic Co-operation and Development (OECD), Paris.

Brahmaputra) and more than double rainfall in the Meghna, and (3) elevated tides in the Bay of Bengal from the monsoon. The third factor did not contribute to runoff, but the elevated tides blocked outflow of the swollen rivers into the Bay of Bengal. The flood inundated close to 100 000 km^2 of land. More than 30 million people were displaced, with 20 million rendered homeless. Hundreds of people were killed directly by the floods, and several hundred thousand cases of diarrhea were confirmed.

There has been a trend in recent decades of much higher interannual variations in flooded areas. As shown in Figure 6, since the late 1970s, flooding events have tended to cover significantly lower or significantly higher areas than had been observed in prior decades. This trend in extremes cannot be simply attributed to climate. Rather several other factors are at play. First, better flood monitoring and control measures have probably contributed to a significant reduction in areal coverage of moderate flooding events, which now cover a much lower area.

Although this is not certain, looking into the future, climate is likely to exacerbate flooding for a number of reasons, including increased glacier melt, increased precipitation, sea level rise, and increased intensities of cyclones, winds, and precipitation.

Higher temperatures will result in more glacial melt, increasing runoff from the neighboring Himalayas into the Ganges and Brahmaputra rivers. Given the altitude of the mountains and the enormous size of the glaciers, this problem will most likely continue over the next century. The problem could be of even greater concern as there is evidence to show that temperatures in the Himalayas (where the glaciers are located) are rising at higher rates, thereby contributing to enhanced snowmelt Mirza and Dixit (1997).

Sea level rise will result in coastal flooding both under ambient conditions (given the low elevations of the coast) and even more so in the event of storm surges. It will also indirectly cause riverine flooding by causing more backing up of the Ganges–Brahmaputra–Meghna rivers along the delta. Assuming a positive correlation between sea surface temperature and tropical cyclone intensity, Ali (1996) calculated the effect of a repeat of the 1991 cyclone with a 2 °C increase (which causes a 10% increase in wind speed) and a 0.3 m sea level rise.

5.23.4 Potential Methods for Remote-Sensing-Based Spatiotemporal Migration Study and Existing Knowledge Base

Analysis of the slum data reported by the Center for Urban Studies (CUS) in Dhaka (in collaboration with the Carolina Population Center at the University of North Carolina in Chapel Hill and the US Agency for International Development, USAID) clearly shows that the continuous increase of the urban slum and squatter settlements has been significantly influenced by the recurrent events of floods. Figure 7 shows the cumulative developments of slum and squatter settlements from the prior years of 1971–2005. Figure 8 shows the association of slum cluster increments with significant flood events. This exploratory analysis indicates that the availability of spatial data for flood inundation, corresponding damage of crops, and migrated settlements can potentially contribute to an

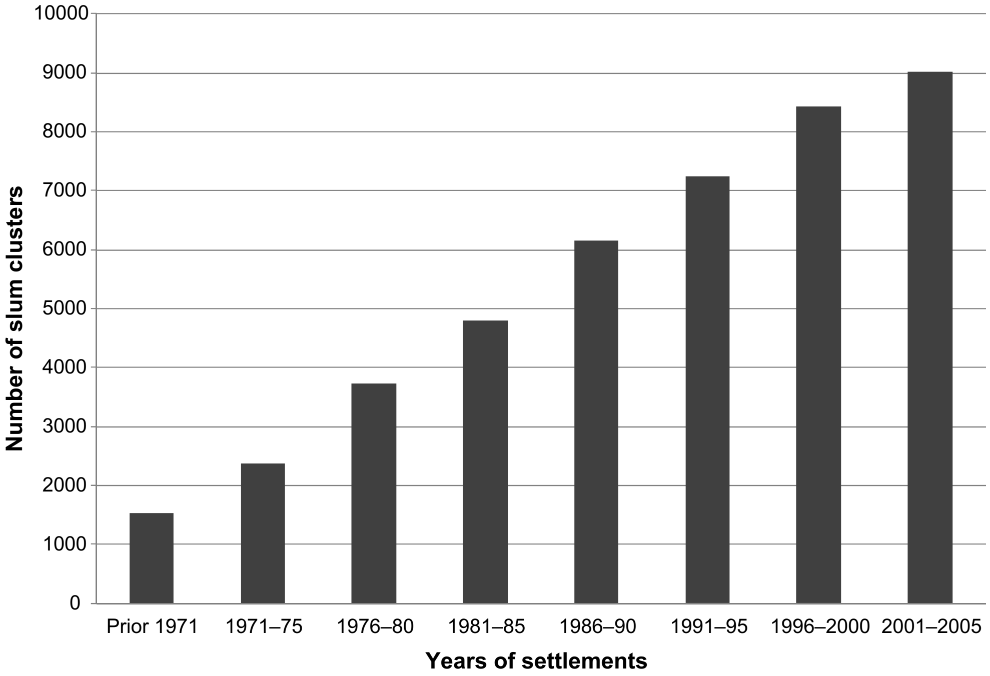


Figure 7 Cumulative developments of slum settlements from the prior years of 1971–2005.

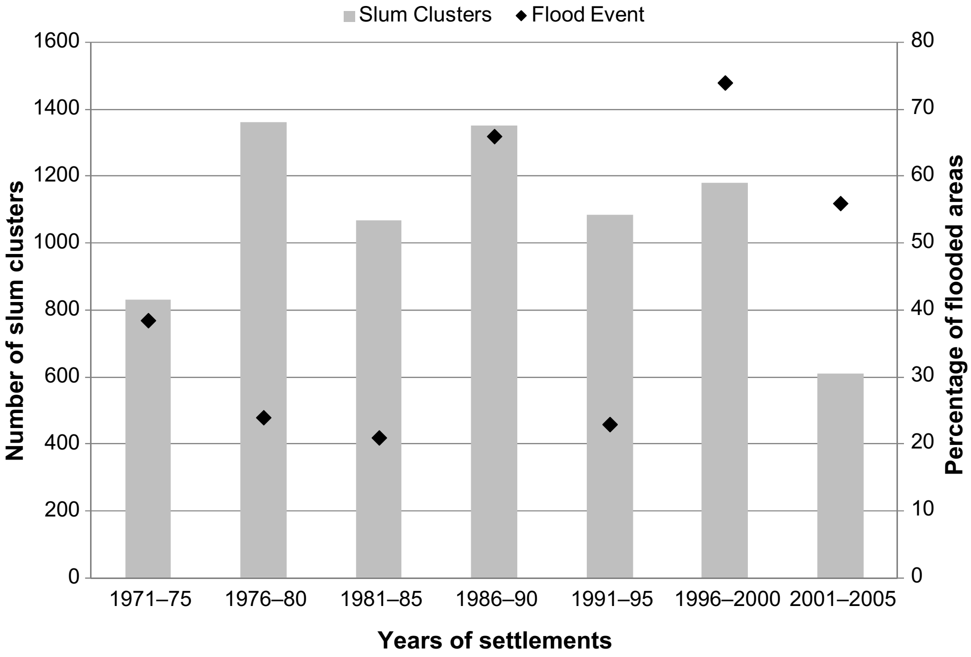


Figure 8 Association of slum cluster increments with significant flood events.

understanding of spatiotemporal migration due to flood. It is strongly believed that the following six tasks can help to accomplish this objective:

Task 1: Preparation of climatologic annual flood inundation maps
Task 2: Validation of satellite-derived inundation maps
Task 3: Multitemporal analysis of flood inundation to detect most flood affected areas
Task 4: Crop damage assessment
Task 5: Preparation of socioeconomic data at the district level
Task 6: Application of socioeconomic models to assess income loss and migration patterns from satellite data

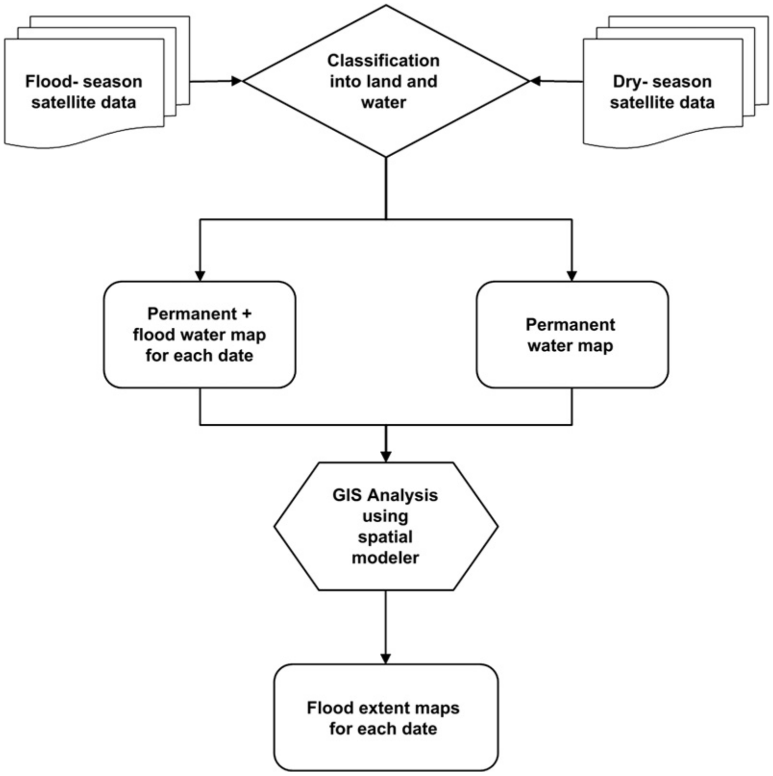

Flood- season satellite data
Classification into land and water
Dry- season satellite data
Permanent + flood water map for each date
Permanent water map
GIS Analysis using spatial modeler
Flood extent maps for each date

Figure 9 Remote-sensing-based model to generate single-date flood extent maps.

5.23.4.1 Preparation of Climatologic Annual Flood Inundation Maps (Task 1)

This step is to generate a series of flood extent maps for selected years from 1980–2010. The proposed task emphasizes the use of NASA Moderate-Resolution Imaging Spectroradiometer (MODIS) satellite imagery (reflectance data) to create the flood inundation maps after 2000 and Advanced Very High-Resolution Radiometer (AVHRR) imagery before 2000. These maps pertain to the monsoon season (Apr.–Aug.). It is expected to have at least 20 such data sets. Figure 9 summarizes the digital image processing and spatial analysis techniques involved in remote-sensing-based flood extent map generation.

Land cover and land use change (LCLUC) studies were conducted using satellite imagery acquired mainly by Satellite pour l'Observation de la Terre (SPOT), Indian Remote Sensing–1D (IRS-1D), and IKONOS (e.g., Dewan and Yamaguchi 2009) and were focused on specific local areas (e.g., Dhaka district). The LCLUC study of this research should use the satellite imagery acquired by Landsat missions since data acquired by Landsat satellites have extensive temporal and aerial coverage, and they can be obtained from USGS free of cost. Since the devastating floods of 1987 and 1988, there has been significant interest in the country regarding research on floods, especially using geographic information systems (GIS) and remote sensing. Flood inundation extent and flood hazard maps were created for targeted flood events using Radarsat-1 Synthetic Aperture Radar (SAR) and Landsat TM (Hossain et al. 2007; Hoque et al. 2011), MODIS, and Radarsat-1 SAR (Islam et al. 2010), AVHRR (Islam and Sado 2000), and SPOT (Blasco et al. 1992) data. The technique explained in Figure 9 was used to generate a flood extent map for part of Bangladesh using a time series of Radarsat-1 SAR imagery acquired between Jul. 2000 and Oct. 2000. Figure 10 shows the flood extent maps for Jul., Aug., early and late Sep., and Oct. 2000.

5.23.4.2 Validation of Satellite-Derived Inundation Maps (Task 2)

The MODIS- and AVHRR-derived flood extent data can be validated using (1) Radarsat-1 SAR-derived flood extent data and (2) hydrodynamic model-derived flood maps. Shuttle Radar Topography Mission (SRTM) and Advanced Spaceborne Thermal Emission and Reflection Radiometer (ASTER)-derived digital elevation maps (DEM) can be used in conjunction with water-level data derived from radar altimeter (TOPEX/POSEIDON/Jason-1 and Jason-2/OSTM).

SAR-derived flood imagery is available at the Center for Environmental and Geographic Information Services (CEGIS) (http://www.cegisbd.com) in Bangladesh for selected years for the entire country of Bangladesh and also at district levels. The Institute of Water Modeling (IWM) (http://www.iwmbd.org) in Bangladesh has already simulated floods for the entire country for different events. In addition to IWM's selected data, the year 2002 was simulated using Hydrologic Engineering Centers River Analysis System (HEC RAS) and the Center for Computational Hydroscience and Engineering–Two Dimensions (CCHE2D) flood model (Jia and Wang 1999; Jia et al. 2002) developed at the National Center for Computational Hydroscience and Engineering (NCCHE) (http://www.ncche.olemiss.edu) can also be used. CCHE2D flood simulation results were compared with different satellite-derived flood

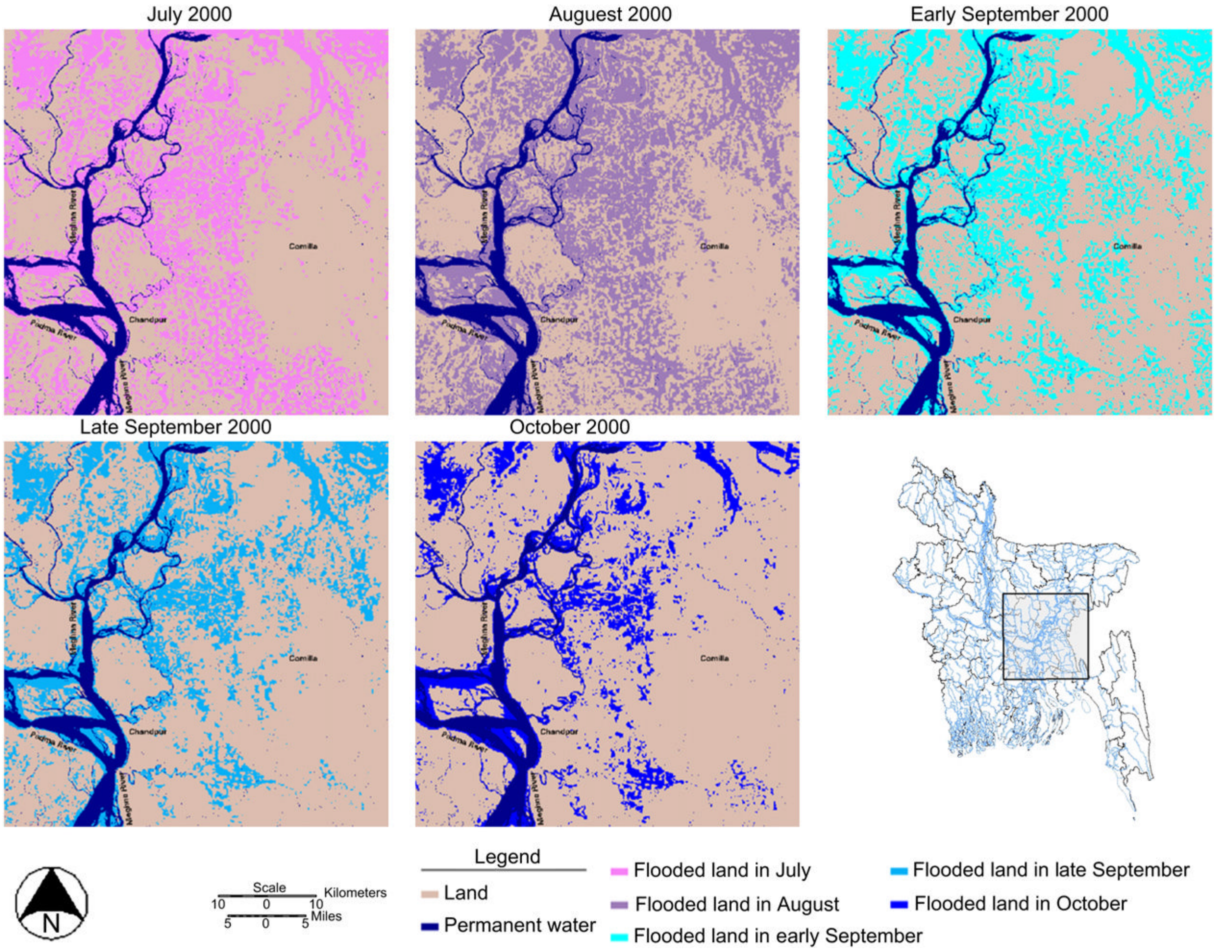

July 2000
August 2000
Early September 2000
Late September 2000
October 2000
Meghna River
Comilla
Chandpur
Padma River
Legend
Land
Permanent water
Flooded land in July
Flooded land in August
Flooded land in early September
Flooded land in late September
Flooded land in October
N
Scale
10 0 10 Kilometers
5 0 5 Miles

Figure 10 A time series of flood extent maps generated for part of Bangladesh for the period between Jul. 2000 and Oct. 2000 using Radarsat-1 SAR and Landsat-5 TM imagery.

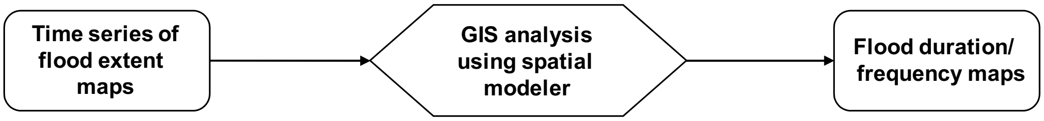

Time series of flood extent maps
GIS analysis using spatial modeler
Flood duration/ frequency maps

Figure 11 Schematic of spatial model for flood duration and flood-frequency map generation.

maps for the 2008 Midwest USA Flood (Hossain et al. 2009). SRTM- and ASTER-derived DEM can be used in conjunction with water-level data derived from radar altimeter (Siddique-e-akbor et al. 2011).

5.23.4.3 Multitemporal Analysis of Flood Inundation to Detect Most Flood-Affected Areas (Task 3)

The goal of this step is to quantify a given flooding season as 'average,' 'below-average,' or 'above average' in a statistical (percentile) and quantitative (using intensity, duration, and extent of flooding) manner. This classification can be done for each district (equivalent to 'states' – there are 64 districts) because other demographic and socioeconomic data are more reliably available at the district level. Then multitemporal analysis can be performed to detect the areas affected by above-average floods and categorize them based on the frequency of flood visit; in this way, a spatiotemporal matrix of flood frequency can be obtained where pixels are categorized as affected by above-average flood for only a single date, two dates, three dates, four dates, up to all dates. Each district can then be categorized using the flood-frequency matrix results. The districts affected regularly by above-average flood can be selected for crop damage estimation and migration studies. Figure 12 shows the flood duration maps obtained from the multitemporal analysis of the time series of the flood extent maps shown in Figure 10. The technique explained in Figure 11 was used to generate this map.

5.23.4.4 Crop Damage Assessment (Task 4)

CEGIS has conducted a few crop damage assessment exercises (i.e., spatial extent of damaged crops in the postcyclone timeframe), such as after Cyclone Aila, from MODIS data using supervised classification incorporating near-real-time ground evaluation of

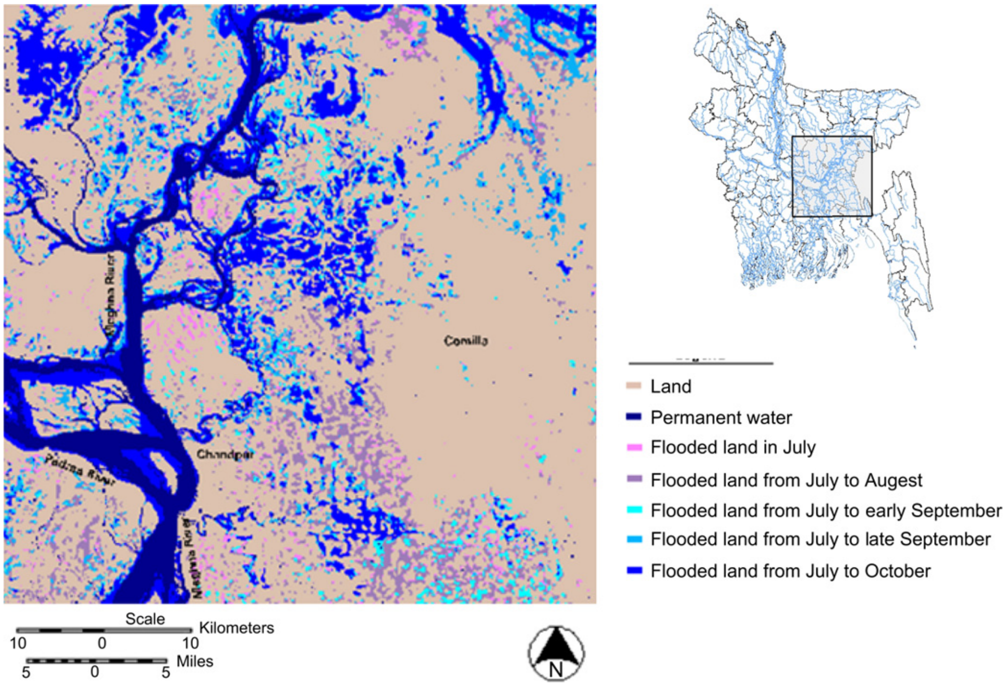

Meghna River
Comilla
Chandpur
Padma River
Meghna River
Land
Permanent water
Flooded land in July
Flooded land from July to Augest
Flooded land from July to early September
Flooded land from July to late September
Flooded land from July to October
Scale
Kilometers
10 0 10
Miles
5 0 5
N

Figure 12 Flood duration and dynamics map generated for part of Bangladesh to study the 2000 flood event using Radarsat-1 SAR and Landsat-5 TM imagery.

the land cover (crop being 'damaged' or 'undamaged'). Hossain et al. (2007) conducted crop damage estimation due to flooding using multitemporal SAR imagery. Figure 13 summarizes the techniques that were used by Hossain et al. (2007).

This technique was applied to map the spatial distribution of the rice crop damage due to the flood that occurred in 2000 (Figure 10). The flood duration and dynamics map for the 2000 flood event (as shown in Figure 12) was used in conjunction with the corresponding crop damage assessment map (as shown in Figure 14), and GIS-based spatial analysis was used to determine the spatial distribution of the damaged crop associated with flood extent and duration. Figure 15 shows the spatial distribution of rice crop damage due to the 2000 flood event in association with flood duration andtrun -1 dynamics. The ground evaluation data acquired by CEGIS can be used in artificial neural network (ANN)-based multisensor data fusion techniques (Pohl and Genderen 1998) using the available optical (Landsat, ASTER, SPOT, and Advanced Land Observing Satellite (ALOS) the Advanced Visible and Near Infrared Radiometer type 2 (AVNIR2)) and microwave (Radarsat-1 and -2 SAR, ENVISAT Advanced Synthetic Aperture Radar (ASAR), ALOS The Phased Array type L-band Synthetic Aperture Radar (PALSAR), and TerraSAR) data over Bangladesh for producing a binary map of 'damaged/undamaged' crops for the areas identified in Task 3 (see Section 5.23.4.3) for each flooding season.

5.23.4.5 Preparation of Socioeconomic Data at the District Level (Task 5)

The socioeconomic data pertaining to migration patterns that is necessary for achieving these research objectives can be obtained from a multilayer archive of Bangladesh government-sponsored

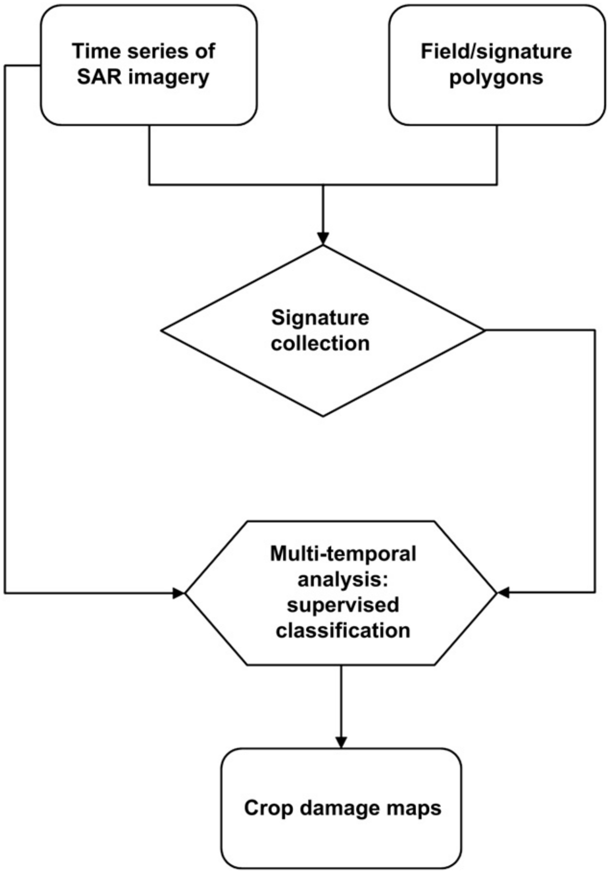

Time series of SAR imagery
Field/signature polygons
Signature collection
Multi-temporal analysis: supervised classification
Crop damage maps

Figure 13 Schematic of a SAR-based crop-damage estimation model (Hossain et al. 2007).

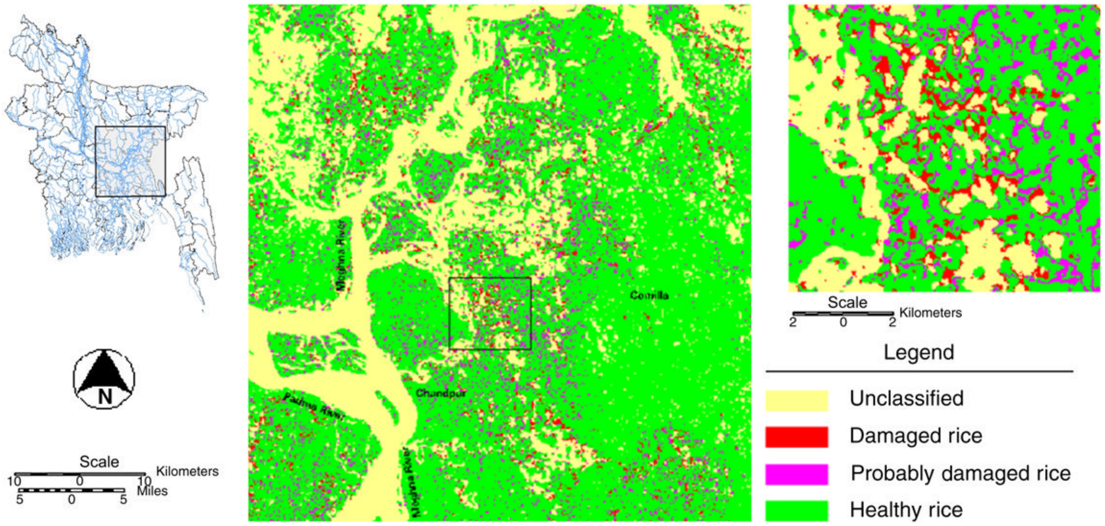

Meghna River
Comilla
Chandpur
Padma River
Meghna River
N
Scale
10 0 10 Kilometers
5 0 5 Miles
Scale
2 0 2 Kilometers
Legend
Unclassified
Damaged rice
Probably damaged rice
Healthy rice

Figure 14 Assessment of rice crop damage for part of Bangladesh during the 2000 flood event using Radarsat-1 SAR data.

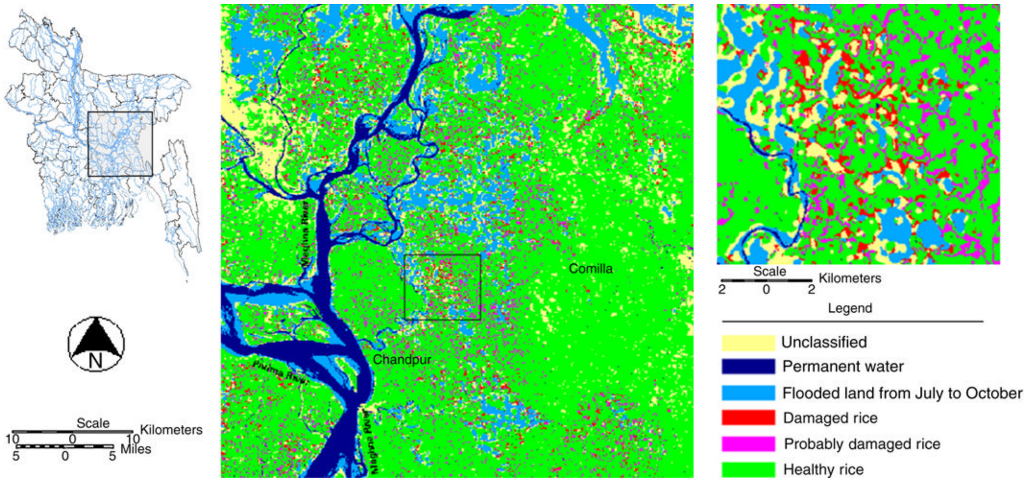
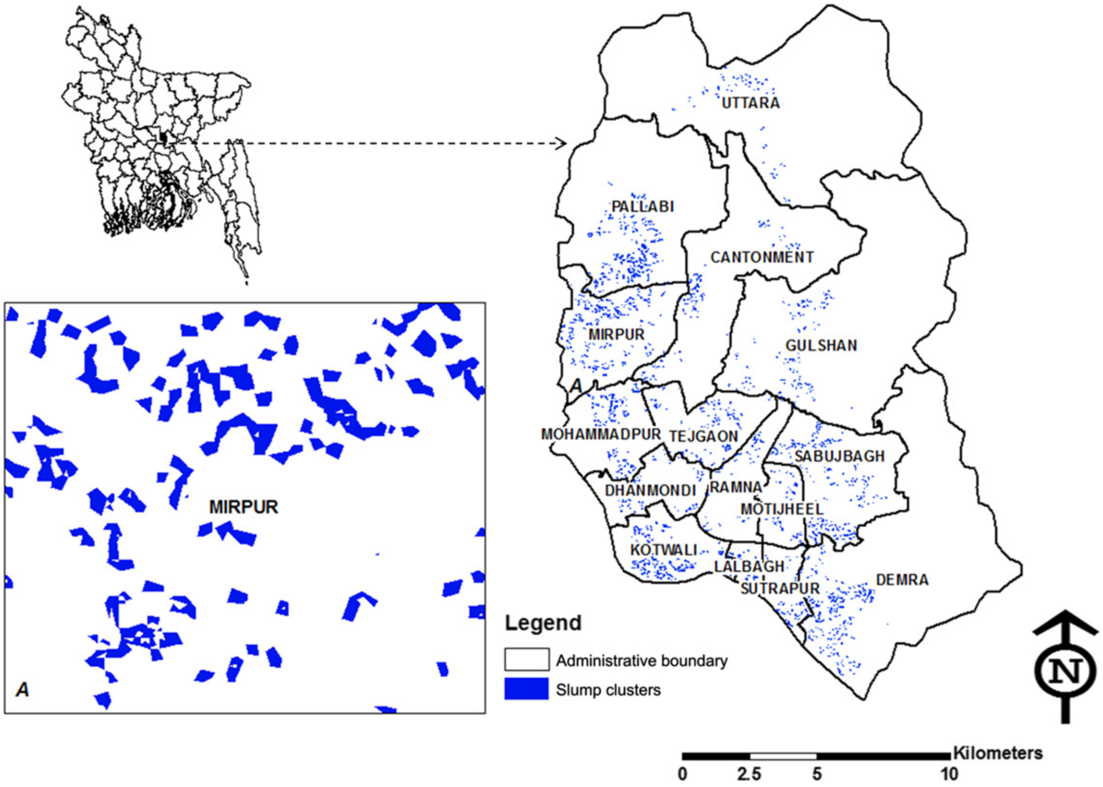

Meghna River
Comilla
Chandpur
Padma River
Meghna River
N
Scale
10 0 10 Kilometers
5 0 5 Miles
Scale
2 0 2 Kilometers
Legend
Unclassified
Permanent water
Flooded land from July to October
Damaged rice
Probably damaged rice
Healthy rice

Figure 15 Mapping rice crop damage and flood water association for part of Bangladesh during the 2000 flood event using Radarsat-1 SAR data.

cross-sectional surveys. Through a strategic partnership with the Bangladesh government and United Nations Development Program (UNDP) agencies, the author has acquired and digitized extensive demographic data produced by the Bangladesh Bureau of Statistics (BBS) from labor force and household surveys. In particular, two comprehensive surveys provide multiyear migration data (comprising in- and out-migration) for each of the 64 districts of Bangladesh along with questionnaire input on reasons for migration. The two BBS surveys that were extensively leveraged for this task are:

1. Preliminary report on household income and expenditure survey (2005, 2010), and
2. Report on sample vital registration system–2009. These statistical data were converted into a GIS database to be incorporated in spatial analysis associated with socioeconomic models.

In Bangladesh, the most common forms of settlements for the migrated population are slums and squatters. In Figure 7 it can be seen that the slums and squatter settlements increased almost 10-fold from 1971 to 2005. Figure 8 shows that the major flood events within this period might have significant influence on the increment of the slums and squatter settlements. In 2005, the Center for Urban Studies (CUS), the National Institute of Population Research and Training, and the Monitoring and Evaluation to Assess and Use Results Evaluation (MEASURE) collaborated to physically identify the boundaries of slums and squatter settlements in the six city corporations of Bangladesh. These slum maps were intended to facilitate the implementation of the urban health survey throughout Bangladesh. Information of the spatial distribution of these slums and squatter settlements should be very useful input for the socioeconomic models to assess migration patterns due to income loss. As an attempt to evaluate the potential of this slum data to be used in spatial analysis, the hard copy of the 1996 slum and squatter settlement map (created by CUS) was digitally processed and put into GIS successfully. The GIS data provided the spatial


UTTARA
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SABUJBAGH
DHANMONDI
RAMNA
MOTIJHEEL
KOTWALI
LALBAGH
SUTRAPUR
DEMRA
MIRPUR
A
A
Legend
Administrative boundary
Slump clusters
N
Kilometers
0
2.5
5
10

Figure 16 Spatial distribution of slums and squatter settlements in Dhaka city as of 1996. extracted from CUS (Center for Urban Studies), 1996: *Survey of Slums and Squatter Settlements (unpublished report)*. Center for Urban Studies, Dhaka.

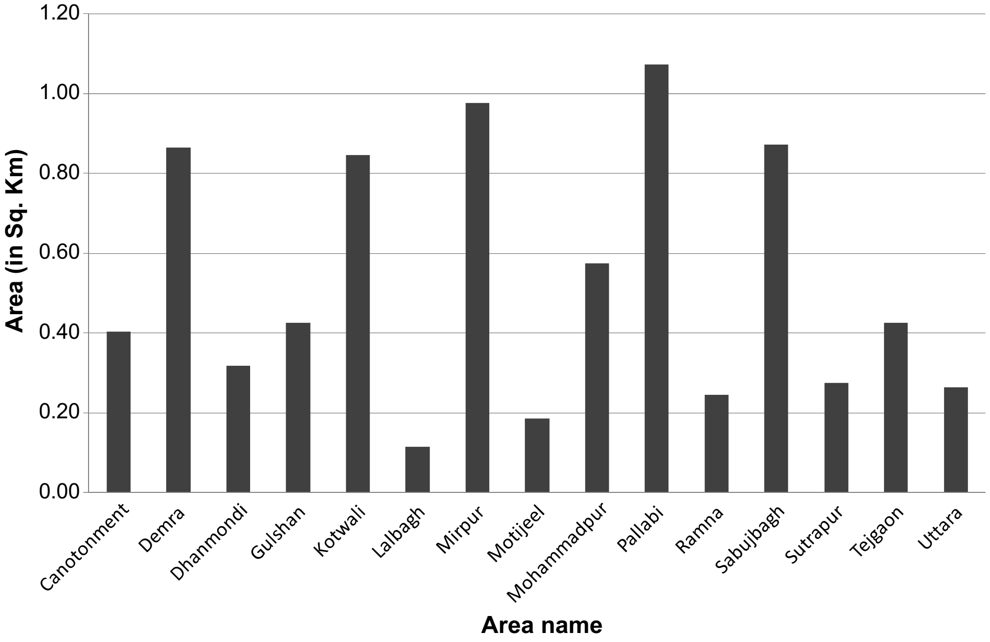

Figure 17 Comparison of slums and squatter settlements in different parts of Dhaka city as of 1996. extracted from CUS (Center for Urban Studies), 1996: *Survey of Slums and Squatter Settlements (unpublished report)*. Center for Urban Studies, Dhaka.

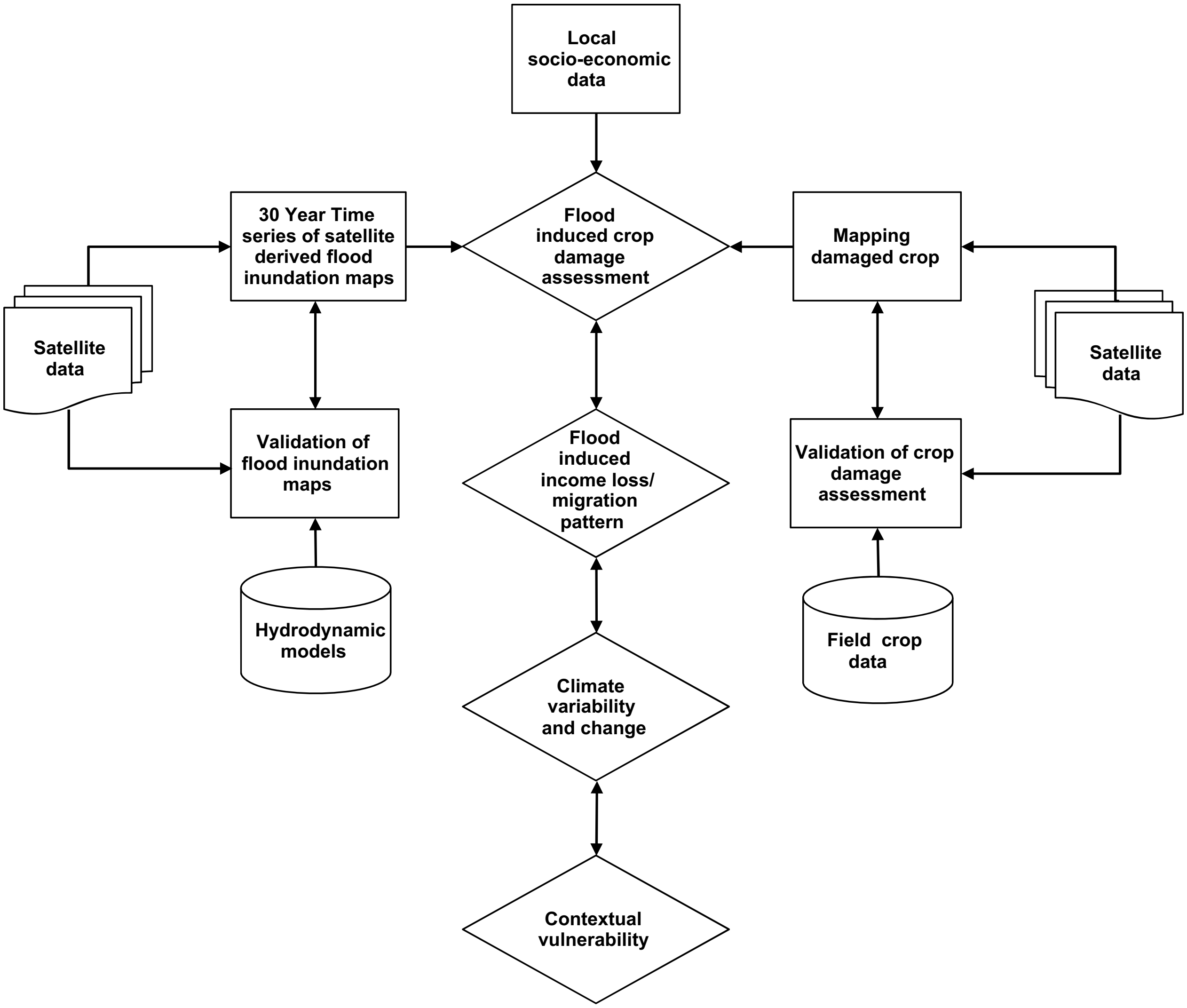
Local socio-economic data
30 Year Time series of satellite derived flood inundation maps
Flood induced crop damage assessment
Mapping damaged crop
Satellite data
Satellite data
Validation of flood inundation maps
Flood induced income loss/ migration pattern
Validation of crop damage assessment
Hydrodynamic models
Field crop data
Climate variability and change
Contextual vulnerability

Figure 18 Potential methods for remote-sensing-based spatiotemporal migration studies and their contributions in contextual vulnerability assessment due to potential climate variability and change with bottom-up perspective as described by Hossain et al. (2011), Pielke et al. (2004) and Pielke et al. (2011).

distribution of slums and squatter settlements for 15 different administrative units of Dhaka Metropolitan City. Figure 16 shows the GIS coverage of the slums and squatter clusters and Figure 17 shows the comparison of areal distribution of these clusters.

5.23.4.6 Application of Socioeconomic Models to Assess Income Loss and Migration Patterns from Satellite Data (Task 6)

In this step, regression relationships (similar to those proposed by Banerjee 2005) can be established. For example, the Banerjee model could be recalibrated and used to predict the loss of rural farmer income from crop damage assessment by remote sensing. Consequently, this loss of income can then be correlated to migration patterns (from the damaged areas to Dhaka city) using protocols outlined in Rayhan and Grote (2007) as well as statistical significance tests. The goal of this step is to identify if frequently available satellite-derived flood-inundation/crop damage assessment can be a reliable proxy for predicting rural-to-urban migration for seasonal and long-term policy and planning. The fitting of equations can be done either in a bootstrapping or cross-validation format or simply using half the data for fitting and the other half for testing predictive accuracy.

5.23.5 Discussion on Potential Scope of Future Research

Potential methods for remote-sensing-based spatiotemporal migration studies and their contributions in contextual vulnerability assessment due to potential climate variability and change with bottom-up perspective (as described by Pielke et al. 2004; Hossain et al. 2011; Pielke et al., 2011) can be summarized by the flow chart shown in Figure 18. The knowledge base achieved with each component of the methods described in the previous section indicates a promising outcome. However, successful completion of each task depends on the availability of good quality data sets and the answers of several open research questions that are discussed as follows.

MODIS has a successful track record of flood inundation mapping. The only issue with the use of MODIS in this regard is having cloud-free imagery. In Bangladesh, during monsoon season it is very difficult to obtain cloud-free imagery. A number of researchers have addressed this problem and proposed several methods to restore the data covered by cloud (Ren et al. 2009a,b). It is believed that adaptation of these methods along with further research could be useful to ensure the use of MODIS data for flood mapping in Bangladesh.

MODIS-derived flood maps were validated using Radarsat-derived flood maps (Islam et al. 2010) for specific years. This validation task should be extended for several additional years to increase the confidence level. SAR-derived flood maps available at CEGIS would be very useful in this regard. The 2008 Midwest US floods were mapped by MODIS imagery and the results were compared with the numerical simulation results obtained from CCHE2D (Hossain et al. 2009). It is suggested that CCHE2D can be used to simulate the 2004 or 2007 flood of Bangladesh and compare the results obtained by Islam et al. (2010) using MODIS imagery. In this case, the model input and boundary conditions data for IWM models can be used.

As suggested by the proposed methods, flooding is to be divided into average, above average, and below average using some basis of statistical criteria. However, an exploration of the potential of using agricultural thresholds (defined by agricultural experience in terms of what it takes to actually affect crop yields) to define the cut-points of flood categories is recommended.

Cropping patterns in Bangladesh are much diversified. It is expected that remote-sensing data fusion techniques incorporating artificial neural networks (ANN) will produce good results. However, since there is no existing research on the application of ANN for mapping cropping patterns in Bangladesh, this task of the proposed methods involves uncertainty. A pilot study can be conducted to evaluate and understand the level of uncertainty that might occur in this task.

The socioeconomic model included in the proposed set of tasks considers generalized migration data. There is very little information about the categories of migration. To model flood-induced migration, it is very important to differentiate among temporary, permanent, and circular migrations. It is also important to separate individual migration from household migration.

Gray and Mueller (2012) recently conducted research to investigate the consequences of climate-related natural disasters for long-term population mobility in selected parts of Bangladesh. This study used survey data from more than 1700 households covering a time span of 15 years to estimate the effects of flooding and crop failures on local population mobility and long-distance migration involving multivariate event history models. The results of this study indicate that flooding has modest effects on population migration that are mainly visible at moderate intensities. This study also found that crop failure due to factors other than flooding had a stronger influence on population mobility, especially for households that are not directly affected but live in severely affected areas. These results clearly imply the need for extending the proposed methods to incorporate models capable of estimating crop failures due to other environmental factors in addition to flooding, such as drought. Like flooding, drought is also studied by remote sensing (e.g., Tucker and Choudhury 1987; Thenkabail et al. 2004). Normalized Differential Vegetation Index (NDVI) and other recently developed vegetation indices have been used to determine vegetation conditions for the assessment of crop yield (Hossain et al. 2006). Several studies investigated the potential of remote sensing techniques to study the impact of agricultural drought on crop yield in Bangladesh (e.g., Shahid and Behrawan 2008; Murad and Islam 2011). Therefore, it is expected that the proposed methods can be easily adjusted to incorporate the impact of drought as a driving factor for crop failure in addition to flooding, and characterize the population migration accordingly.

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5.24 Adaptation Strategies for Water Resources Management in Bangladesh from Risks of Climate

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5.24.1 Introduction

Bangladesh is located in the alluvial, deltaic floodplain in the confluence of three major rivers: the Ganges, the Brahmaputra, and the Meghna. Water is the basis of living for the country's population. However, Bangladesh is located in a region that is considered as one of the most disaster prone areas in the world. Frequently, the country faces the challenge of severe flooding, drought, and cyclone-induced storm surges. Significant river bank erosion is a regular phenomenon along the large rivers. The southern part of Bangladesh is subjected to saline water intrusion in the surface as well as the groundwater systems. With increased development and population, water management has become more complicated (Haque 2008). The impacts of climate further complicate the situation. Hereafter in this chapter, as outlined in the foreword of the encyclopedia, the term 'climate' will be considered as inclusive of both change (first order moment) and variability (second order moment) within the known statistical distribution. The term 'change' will be used after climate only when a change in statistical distribution is being explicitly referred to.

Bangladesh is globally known as one of the most vulnerable countries to climate risks. The risks from climate can potentially exacerbate many of the current problems and natural hazards the country faces. Inferring from model projections alone that are outlined in the Intergovernmental Panel on Climate Change (IPCC) AR4 report, which, however, cannot be validated since they refer to the future, the following two key points summarize the current perception of climate risks in Bangladesh among policymakers: (1) floods, droughts, tropical cyclones, and storm surges are likely to become more frequent and severe in coming years (IPCC 2007); (2) sea level rise (SLR) could cause delay in flood recession, increase storm surge heights, and lead to salinity intrusion further inland. If these climate projections are overwhelmingly relied on, one may surmise that the water sector in Bangladesh is expected to be significantly affected and that it is necessary to develop and adopt an effective adaptation strategy. However, this chapter will show that a contextual overview of the key issues affecting

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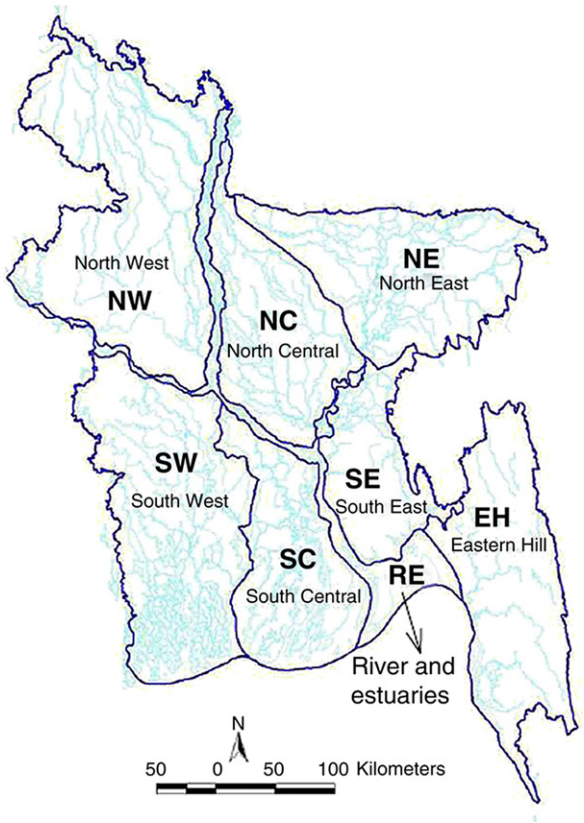


Figure 1 Hydrologic regions of Bangladesh.

water resources of Bangladesh will indeed be significantly affected from a myriad of other factors beyond those from climate risks and that it is critical to have a broader and more 'bottom up' view for formulating an effective adaptation strategy.

In this chapter, we first provide a contextual background to the important role water resources play in Bangladesh. The key environmental and socioeconomic variables that affect the country's water resources are discussed along with the sensitivity of water resources to key variables. Then, for the most sensitive variables, critical changes (thresholds) are described with associated probabilities. After that, measures that have been implemented or planned to eliminate negative impacts on the country's water resources are discussed. The chapter concludes with specific recommendations for policymakers and key stakeholders for adaptation from a bottom-up resource perspective.

5.24.1.1 Importance of Water Resources in Bangladesh

Bangladesh can be divided into several hydrologic regions (see Figure 1). The key water resources features, uses, and threats for each of the hydrologic regions are summarized in Table 1.

5.24.1.1.1 Role in Nutritional Needs (Food Security)

Bangladesh's economy is still dominated by the agriculture sector, in which irrigation production plays an important role. The food produced, mainly rice, is not only important for nutritional needs of the growing population (see Figure 2) but also valuable export income. The water

Table 1 Key water resources features, uses, and threats by hydrologic region

	SW	*NE*	*NC*	*NW*	*SC*	*SE*	*EH*	*RE*
Water Resources Features								
Monsoon floods	✓	✓	✓	✓	✓	✓		✓
Tidal floods	✓				✓	✓		✓
Flash floods		✓				✓	✓	
Storm surges	✓				✓		✓	✓
Drought prone	✓			✓	✓			
Drainage congestion								
Main Uses (Demands)								
Irrigation	✓	✓	✓	✓	✓	✓	✓	✓
Urban and rural water supply	✓	✓	✓	✓	✓	✓	✓	
Ecosystem services	✓	✓	✓		✓	✓	✓	✓
Navigation	✓	✓			✓	✓	✓	✓
Capture fisheries		✓						✓
Hydropower							✓	
Threats to Resources and Livelihoods								
Increasing water demands		✓	✓			✓	✓	
Pollution	✓		✓			✓	✓	
Arsenic in GW	✓	✓			✓	✓		
Salinity intrusion	✓				✓		✓	✓
Upstream flow changes	✓	✓		✓		✓		✓
Groundwater mining			✓					
River bank erosion								✓

Institute of Water Modeling, Bangladesh (www.iwmbd.org).

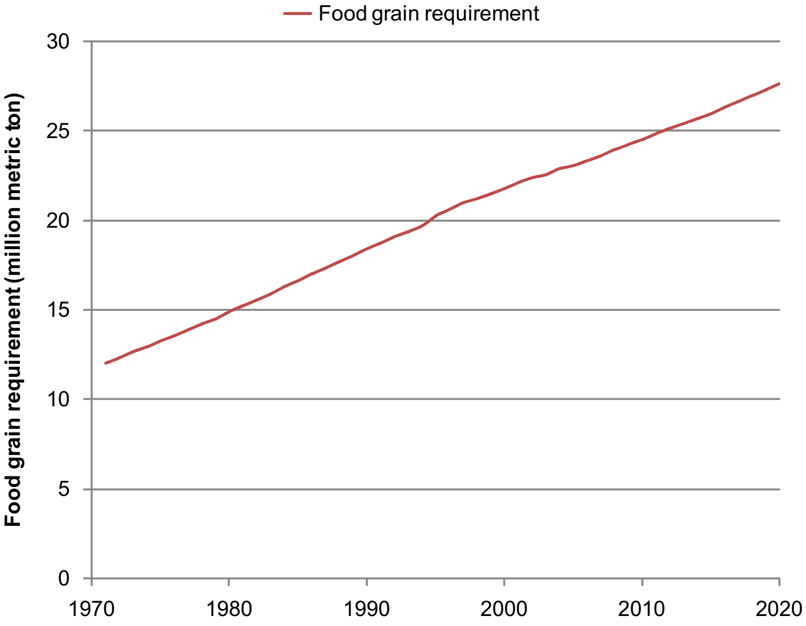


Figure 2 Food grain requirements of Bangladesh. Ministry of Agriculture. MoA, 2007: *Handbook of Agricultural Statistics*, December 2007, Ministry of Agriculture, Government of the People's Republic of Bangladesh. [Available online at http://www.moa.gov.bd/statistics/statistics.htm.]

resources also play an important role in fisheries production (Figure 3). The total annual fisheries production is above 2 million tonnes year^{-1} (FAO 2012). Although production from culture fisheries (fish farms) is now dominating open-water ('capture') fisheries, the total production supports the protein needs of the population and also generates significant export income (Haque 2008).

5.24.1.1.2 Role in Water Supply

With population growth, urban and rural town water demands continue to increase. Water supply tends to be from groundwater aquifers, which are being mined in and around the major cities. However, presence of arsenic in groundwater requires a shift toward surface water resources. The seasonal nature of surface water resources and the fact that most of these resources are from transboundary rivers presents other water management challenges (WARPO 2001). About 79% of the total water used in the country is from groundwater and the remaining from surface water sources (FAO 2010).

5.24.1.1.3 Role in Economic Development

Bangladesh has managed to maintain solid economic development of the last 10–20 years (MoF 2010). Water resources have played an important role via the agriculture sector and also some water intensive manufacturing and industrial sectors. On the other hand, unchecked and rapid development in certain locations has led to acute water pollution problems. Inland water transportation is also an important communication mode in some regions. Further details in this regard can be found in Haque (2008).

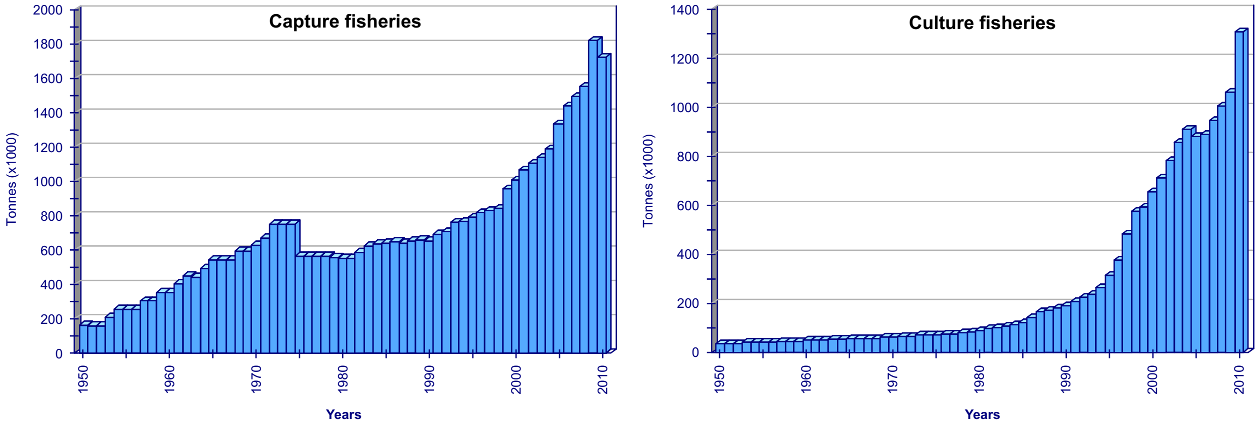


Figure 3 Fisheries production of Bangladesh. FAO, 2012: *Fishery and Aquaculture Country Profiles – Bangladesh*. Food and Agriculture Organization. [Available online at http://www.fao.org/fishery/countrysector/FI-CP_BD/3/en.]

5.24.1.1.4 Role in Ecosystem Services

The vast rivers, fertile floodplains, coastal estuaries, and eastern hills provide a richly biodiverse ecosystem. These include tropical evergreen rainforests, moist deciduous forests, mangrove forests, riparian and coastal wetlands, and the littoral, sublittoral, and benthic communities of the Indian Ocean (IUCN 2000). These ecosystems heavily depend on the monsoon rainfall, fresh river water, and the brackish coastal water resources. However, the growing population is stretching the natural resources of Bangladesh. For example, the Sundarbans forest, along the Indian border, is the largest remaining mangrove forest in the world. Several rare species of flora and fauna live in these wetlands. The Sundarbans also provides protection from storms and cyclones. However, this forest ecosystem is threatened by lack of upstream freshwater and salinity intrusion from the south.

5.24.1.1.5 Role in Natural Disasters

Bangladesh is located at the tail-end of the Ganges–Brahmaputra–Meghna (GBM) basins covering an area of around 1.72 million km^2 (Ahmad et al. 2001). Around 97% of the basin area is located outside of Bangladesh. The rivers of Bangladesh carries on an average of 180 000 m^3 s^{-1} of peak monsoon flow and 80% of the flow is generated from rainfall and snowmelt in the upstream river basins. The topography is generally flat except for the hilly terrains in the north- and southeastern parts of the country. Two-thirds of the land area of Bangladesh is less than 5 m above mean sea level. As a result, the country is susceptible to frequent inundation from rainwater and river floods (see Figure 4). Every 3–5 years, floods of devastating magnitudes inundate nearly about two-thirds of Bangladesh. Furthermore, storm surges due to cyclones also lead to flooding and salinity intrusion in coastal areas. For more information, the reader is referred to Brammer (1999) and Haque (2008).

River bank erosion is another source of disasters for the town and settlements located in and around the large rivers. Some people are forced to migrate to the cities because of river erosion. Others, especially those living on chars (sand bars), have become masters of adaptation and have a rich indigenous knowledge of the local area to cope during such disasters.

5.24.2 Sensitivity of Water Resources to Environmental and Socioeconomic Variables

Based on the previous section, the key environmental and socioeconomic variables affecting water resources in Bangladesh are summarized in Figure 5.

The relative sensitivity of water resources to the above variables are summarized in Table 2. The sensitivity is considered in two dimensions: spatial extent (i.e., How prevalent is its influence throughout the country?), and temporal extent (i.e., Is the sensitivity seasonal or more persistent?). The sensitivity has been qualitatively assessed by the authors by searching published literature and is reported at three levels: high, medium, and low.

5.24.2.1 Climate and Weather

The water resources of Bangladesh are very sensitive to the climate, which is dominated by the Indian Ocean Monsoon system. There are four meteorological seasons: premonsoon/summer (March–May), monsoon (June–September), postmonsoon (October–November), and dry/winter (December–February). Average annual rainfall is around 2300 mm,

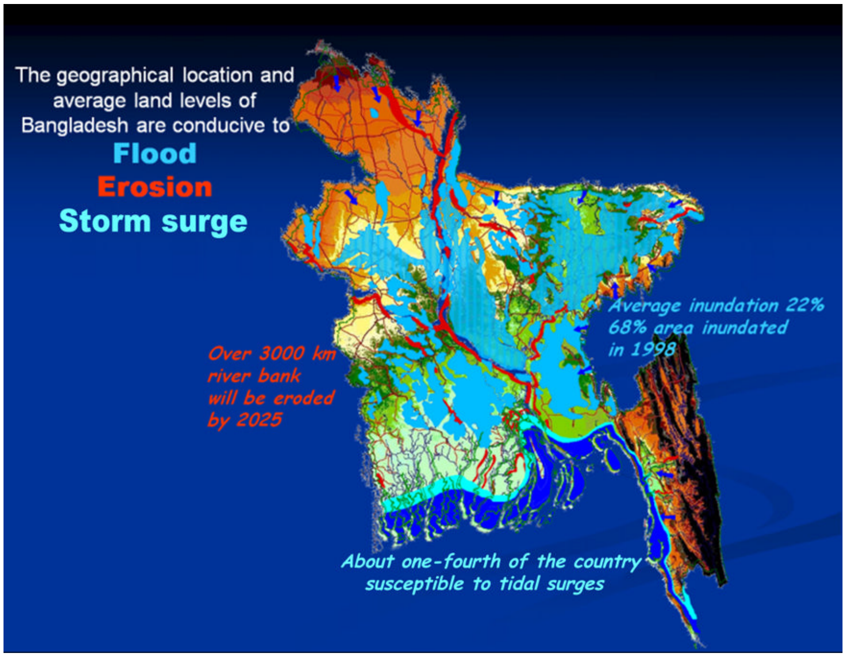

The geographical location and average land levels of Bangladesh are conducive to
Flood
Erosion
Storm surge
Average inundation 22%
68% area inundated in 1998
Over 3000 km river bank will be eroded by 2025
About one-fourth of the country susceptible to tidal surges

Figure 4 Location and extent of selected natural disasters affecting Bangladesh. Note: Projections on river bank erosion based on current rates of erosion records observed by IWM. Institute of Water Modeling, Bangladesh (www.iwmbd.org).

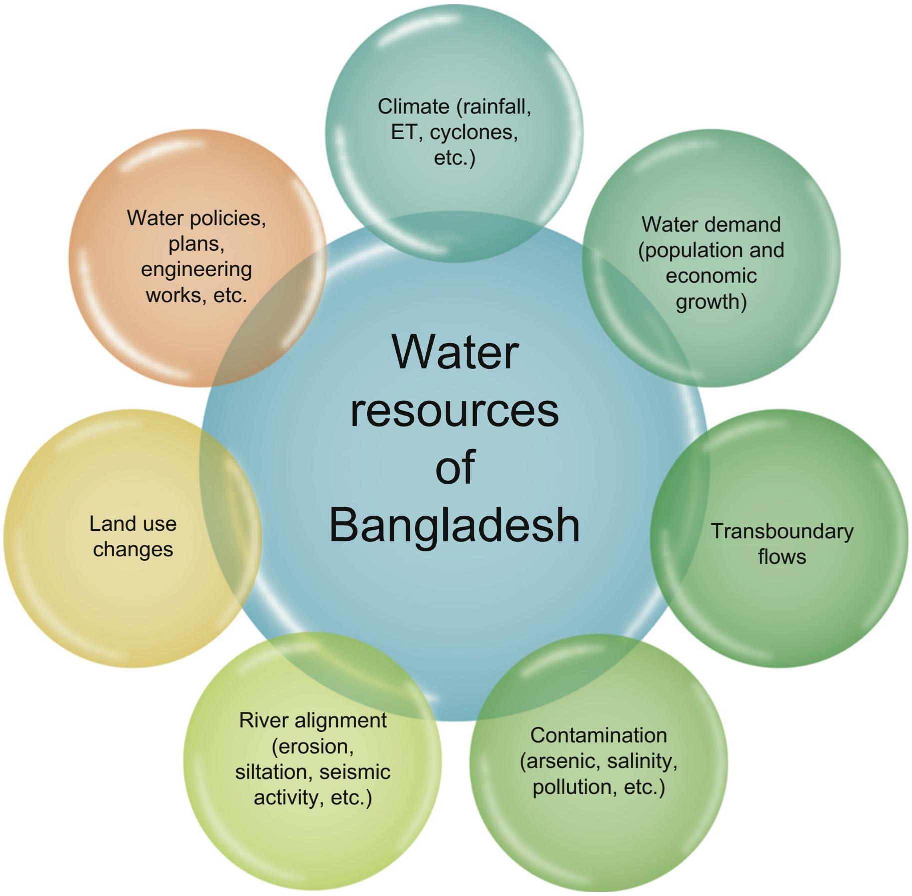

Climate (rainfall, ET, cyclones, etc.)
Water policies, plans, engineering works, etc.
Water demand (population and economic growth)
Water resources of Bangladesh
Land use changes
Transboundary flows
River alignment (erosion, siltation, seismic activity, etc.)
Contamination (arsenic, salinity, pollution, etc.)

Figure 5 Key variables affecting water resources of Bangladesh.

Table 2 Sensitivity of water resources to environmental and socioeconomic variables

	Sensitivity of Water Resources		
Variable	*Spatial Extent*	*Temporal Extent*	*Remarks*
Climate and weather	H	H	Monsoon leads to 5 months wet season and 7 months dry season
Transboundary flows	H	H	~97% of GBM basins area located outside Bangladesh
Water demand	H	M	Large growing population and economic development increasing demands
Water policies, plans, etc.	M	H	Implementation hindered by lack of capacity at local to national level institutions
Contamination	M	M	Localized problem around industrial areas and cities/townships, particularly in dry season; arsenic problem in some regions
River alignment	M	L	Erosion and accretion affects the course of regional rivers, occurring in postmonsoon and dry seasons
Land use changes	L	L	Urbanization and other land use changes affecting runoff patterns

H = high, M = medium, L = low.

varying from 1110 mm in the northwest to 5690 in the northeast (FAO 2010). About 70% rainfall occurs during the period from June to September. Mean monthly rainfall during the same period is between 300 and 450 mm. Average humidity is close to 90% in the monsoon season (FAO 2010).

Changes in timing of the monsoon and its intensity have a major bearing on the state of water resources and consequential effects on agricultural production and other economic sectors. For example, if the monsoon arrives too early, then flash floods can occur and crops (Boro rice) can be damaged in low-lying areas (Brammer 1999; Chowdhury and Ward 2007).

Other weather events such as cyclones have major impacts on water resources in the coastal region. Storm surges during cyclones cause flooding and increased salinization in coastal areas. The coastal region of Bangladesh, covering an area of 4 million ha, is extremely vulnerable to cyclone-induced storm surges. Between the years 1877 and 2010, Bangladesh was hit by 160 cyclone events – of them 45 were severe. The severe cyclone events generated storm surges, which were sometimes more than 10 m in height. This has major impacts on infrastructure, agricultural production, and water supply.

Drought is particularly common in the Northwest region during November to April. During this period, only 20% of annual rainfall occurs and most of the regional river loses its connectivity with the major rivers. Moreover, withdrawal of water by upstream nations from the international rivers is a major problem to the sustainability of dry season flow in these rivers. Monsoon drought is also common due to active monsoon breaks. Also, extensive periods of hot weather in the summer lead to peaks in water demand, especially in the irrigation sector (WARPO 2001).

5.24.2.2 Transboundary Flows

In addition to the seasonal nature of the river flows, upstream interventions on transboundary rivers have major implications on the water resources of Bangladesh. About 97% of the GBM basins area located outside of the country. There are 57 transboundary rivers, of which 54 are shared with India and the remaining 3 with Myanmar. Similarly, many aquifers are located on both sides of the international borders. With heavy reliance on groundwater in the region due to growing water demands, particularly in the dry season, the water resources in Bangladesh are very sensitive to changes in abstraction from these aquifers (Haque 2008).

5.24.2.3 Water Demands

An increasing demand for both surface and groundwater comes from irrigation, which accounts for approximately 58% of the total demand for water (Chowdhury 2010). Fisheries, navigation, and environment sectors account for approximately 41%, while demand for household and industrial use is about 1% (Chowdhury 2010). Meeting the growing water demand in the country, driven by population growth and overall economic development, is a major challenge for water managers. In cities like Dhaka, Chittagong, and Khulna, the water supply authority is looking at tapping sources from further and further rivers. In particular areas, like Dhaka, excessive groundwater pumping has lead to significant falls in the water table. Even though Bangladesh is blessed with many rivers, the seasonal flow pattern makes it difficult to match water demands in the dry season. In order to meet the growing food demands of the population, irrigated agriculture is being intensified in various parts of the country. As a result, the water resources of the country are particularly sensitive to the changing nature and seasonality of water demands. This is one of the reasons why particular policies, plans, etc. are put forward.

5.24.2.4 Water Policies, Plans, etc.

The national water plans (NWP) of 1987 and 1988 were initiated by the government to prepare a comprehensive water master plan with a planning horizon up to 1990–2010. Despite the many limitations of the plans, both phases of the NWP made vital contributions to the knowledge and understanding of the water resources of Bangladesh.

After the disastrous floods of 1987 and 1988, a number of studies on the flood problem of Bangladesh were carried out under the flood action plan (FAP). The rehabilitation and improvement of existing schemes, rather than new development, was given attention in FAP. The FAP Summary Report, published in December 1995, presented a proposed framework and short-term (1995–2000) program for future development. This implementation program centered on the completion of FAP activities, flood proofing, river management and coastal protection, urban flood control and drainage (FCD), and water and flood management. The Bangladesh water and flood management strategy (BWFMS) was the major strategy follow-up to FAP and became the working policy document for the water sector. Many of the BWFMS concepts were carried forward into the National Water Policy, which was adopted in December 1998. The concepts advocated a more multisectoral integrated approach, which was a substantial deviation from the ideas that had dominated water sector thinking until the early days of FAP. National Water Policy insists on regional cooperation to adapt with the vulnerability of floods, drought, and cyclone through developing a system for exchange of information and data on relevant aspects of the management of flood and drought.

The National Water Resources Council (NWRC) is the highest national body for the formulation of water policy. The NWRC coordinates different water agencies and makes recommendations on all water policy issues to the cabinet. The Ministry of Water Resources plays a major planning role through the Water Resources Planning Organization (WARPO) and project implementation through the Bangladesh Water Development Board (BWDB). Other key organizations with policies, plans, projects, etc. related to water resources include the Department of Public Health Engineering (DPHE), the Local Government Engineering Department (LGED), the metropolitan Water and Sewerage Authorities, the Department of Fisheries, Bangladesh Inland Water Transport Authority (BIWTA), the Roads and Highways Department, the Department of Environment (DoE), and respective municipal authorities. The BIWTA is responsible for the maintenance of river navigation channels.

Various national level policies, plans, and projects have major influences on water resources in the country. For example, the National Water Policy and National Water Management Plan address key issues in the water sector. However, full implementation of all key policies and plans have been generally difficult for various reasons, e.g., funding limitations, lack of institutional capacity, resistance from different interest groups, etc. Also, a lack of integration of polices and plans related to water resources hinders positive outcomes.

5.24.2.5 Contamination

Water resources of Bangladesh are sensitive to contamination by human practices and also from natural sources. Rapid economic development and a general disregard for environmental stewardship have lead to contamination of surface and groundwater resources. The situation becomes particularly bad during the dry season. Although the monsoon flows help dilute pollution levels in surface water resources, groundwater contamination persists throughout the year. The presence of arsenic in groundwater from geological formations in various regions around the country is an example of natural contamination. There is also contamination caused by a combination of human actions and natural processes. For example, salinity intrusion in coastal rivers, mainly a dry season phenomenon, is affected not only by upstream flow changes but also by natural advection and dispersion processes (RRI and SWMC 1993).

5.24.2.6 River Alignment

The delta that forms Bangladesh is still active and there are high rates of erosion and sedimentation, which regularly alters river alignment in various parts of the country. Thus, changes in river alignment also affect water resources in Bangladesh. For example, anabranches and bends get cut off due to silt deposits creating lakes. Also, distributaries get cut off due to siltation at outfalls from the main channel and there are no freshwater flows into that channel. This is the case of the Gorai River, which is cut off from the Ganges River for about 5 months of the year and this results in significant salinity intrusion into in the Southwest region. Erosion can also lead to shifts in flow from one channel to other channels. Changes in river alignment tend to occur in monsoon (due to erosion) and postmonsoon (due to sedimentation) times (Mohiuddin 2011).

5.24.2.7 Land Use Changes

In various parts of the country, water resources are being affected by land use changes in catchment areas. Agricultural land is being converted to residential and industrial land due to developmental pressures. This is particularly prevalent near urban growth centers. These changes not only impact surface runoff patterns but also affect groundwater recharge processes. Also, agricultural land has been converted to roads and are built on embankments, which has impacted flow patterns in floodplains. In eastern regions, clearing of forests and cutting of hills are impacting the runoff process. These changes are not extensive compared to the total area, and the temporal extent of impacts on water resources are generally seasonal or of shorter duration (Haque 2008).

5.24.3 Critical Changes (Thresholds) in Variables Affecting Water Resources

As discussed in the previous section, the water resources of Bangladesh are particularly sensitive to changes in the following variables:

- Climate and weather
- Transboundary flows
- Water demand
- Water policies, plans, etc.
- Contamination

In this section, critical changes in each of the above variables are identified and discussed. A simple framework for identifying when and where changes are critical has been used (see Figure 6). The framework takes into account variability (seasonal and long term) in environmental variables (e.g., flood flows) and also changes (short- and medium term) in socioeconomic variables (e.g., population growth). These factors are then considered in a spatial context, e.g., large flood flows in areas with relatively low population densities are less critical than those in high population density areas. The combination of these spatial and temporal factors combine to determine whether a change in the variables affecting water resources are critical or not, i.e., whether the change results in significant risks or hazards on the water resources.

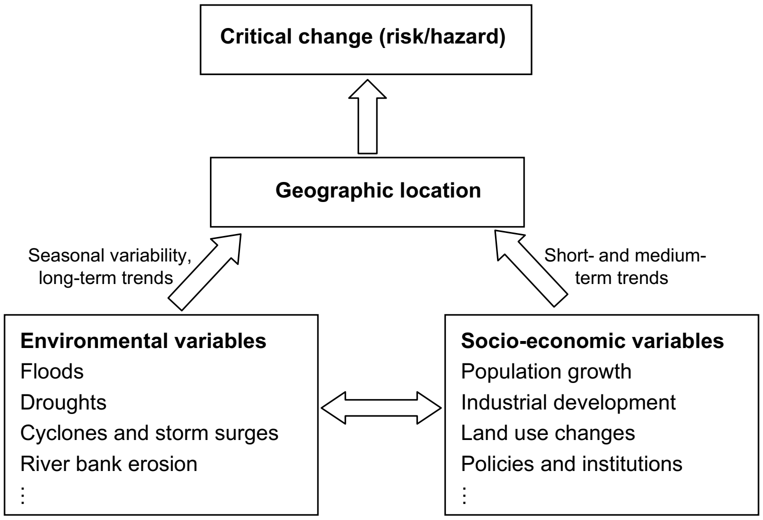


Figure 6 Framework for identifying critical changes in variables.

Where possible, particular thresholds that lead to positive (or negative) impacts on water resources are highlighted from published literature or ongoing studies. Where appropriate, critical changes to the state of the water resources have been investigated using a set of computer models. A brief description of the models used is given in Table 3.

5.24.3.1 Climate and Weather

An overall increase in the mean seasonal rainfall has been observed for all seasons, except for the monsoon season (CCC 2009). Similar findings were reported by Rahman et al. (1997), Singh and Sontakke (2002), and Mondal and Wasimi (2004). These decreasing monsoon and increasing winter rainfall trends are contrary to IPCC's (2007) AR4 projections. A more detailed study of rainfall patterns suggests a decrease in the early part of monsoon (June–July) and an increase in the later months (September–October) (CCC 2009). Thus, a shifting of seasons could be occurring. Also, there is evidence of increased intensity of monsoon rainfall along the path of the south–westerly monsoon winds (over Chittagong, Sylhet, Mymensigh, and Bogra) (CCC 2009). These changes in the monsoon timing have major impacts on the cropping cycle and also on fish breeding patterns.

The frequency of extreme rainfall events has also increased over the recent years. The highest recorded rainfall for any month in the capital for a 24-h period was 341 mm in September 2004. Again, more recently, 448 mm of rainfall was recorded during 24 h in Dhaka on 27 July 2009, which was the highest recorded event in the capital. In fact, 290 mm of rainfall was recorded during 8 h from 11 pm on 27 July to 7 am on 28 July 2009. The previous 24-h record for Dhaka in July was 326 mm in 1956. The increasing frequency of extreme rainfall events is leading to increased localized flooding especially in urban areas and flash-flood prone areas in the Northeast region (Rahman et al. 2005; CCC 2007).

Analysis of temperature from different stations in Bangladesh from 1948 onward shows a clear sign of change and variability (see Figure 7). Khan et al. (2000) analyzed sea-surface temperatures (SST) for May and November (cyclone seasons) at two coastal stations for the period 1985–98. At Hiron Point, the average temperatures increased by 1 and 0.5 °C in May and November, respectively. At Cox's Bazar, the corresponding SST increased by 0.8 and 0.4 °C. In a more recent study, Bangladesh's Climate Change Cell (2009) also reported that mean temperatures across the country have been increasing for all seasons. It is interesting to note that the temperature increase is higher in a more recent period compared to the longer period, as shown in Table 4. It should be noted for future policymaking, that more rigorous statistical analyses (such as *t*-test, Mann–Kendall test, etc.) are required to establish where this change is significant before formulating any strategy.

Temperature increases in the Himalayan region will be critical for water resources in Bangladesh. This is because the corresponding increase in snowmelt will lead to more runoff from mountain regions. When this is added to an increasing trend in monsoon rainfall, the flooding situation in the country can considerably worsen.

5.24.3.2 Transboundary Flows

Around 80% of flow through Bangladesh originates from upstream catchments in India, Nepal, Bhutan, and China. The Ganges, Brahmaputra, and Meghna (GBM) rivers carry this flow through Bangladesh to the Bay of Bengal. The combined discharge of water from the GBM rivers is second only to that of the river Amazon. These rivers discharge 1.5 $\mathrm{Mm^3\,s^{-1}}$ during the peak period (Hasan and Mulamoottil 1994). In the low season, the runoff is only about 61 000 $\mathrm{m^3\,s^{-1}}$ (Hasan and Mulamoottil 1994). The ratio of peak to low season flow is approximately 25:1. Almost 85% of the mean dry season stream flow is found in the GBM rivers (World Bank 2000). The Brahmaputra accounts for 67% of the flow measured within the country, whereas the share of the Ganges is only 13% (Hasan and Mulamoottil 1994). The Meghna contributes only 2% of the total measured discharge in Bangladesh during March.

Analysis of trends in the river flow in the GBM rivers is not straightforward because sufficient data are not available to

Table 3 Models used to analyze critical changes in water resources

Model	*Description*
Model of the GBM basins	The model covers the entire area of the GBM river basins of 1.64 million km^2 and extends into India, Nepal, Bhutan, and China. This model has been used to simulate the changes to the transboundary flow into Bangladesh. The projected rainfall and temperature from the General Circulation Models has been used as input to the basin model to project the inflow from the basins into Bangladesh assuming hypothetical scenarios that cannot be validated.
Hydrodynamic model of Bangladesh – the super model	The super model of Bangladesh is a detailed hydrodynamic model of all significant rivers and the floodplain system of Bangladesh. The inflow predicted by the GBM basins model has been used as a boundary condition for this model. This model simulates water level and discharge in the river system at 12 000 computational grids. The geographic information system interface allows for generating the flood maps. The downstream (sea boundary) boundary conditions are tidal water levels generated by adding the SLR with the actual or computed tidal water levels.
Salinity intrusion model	The salinity model covers the entire tidal area of Bangladesh. The model can simulate salinity concentration at various locations. This model takes the upstream inflow and downstream tidal boundary as boundary conditions. Impacts on salinity concentration due to any change to the upstream and downstream boundary conditions can be simulated by this model.

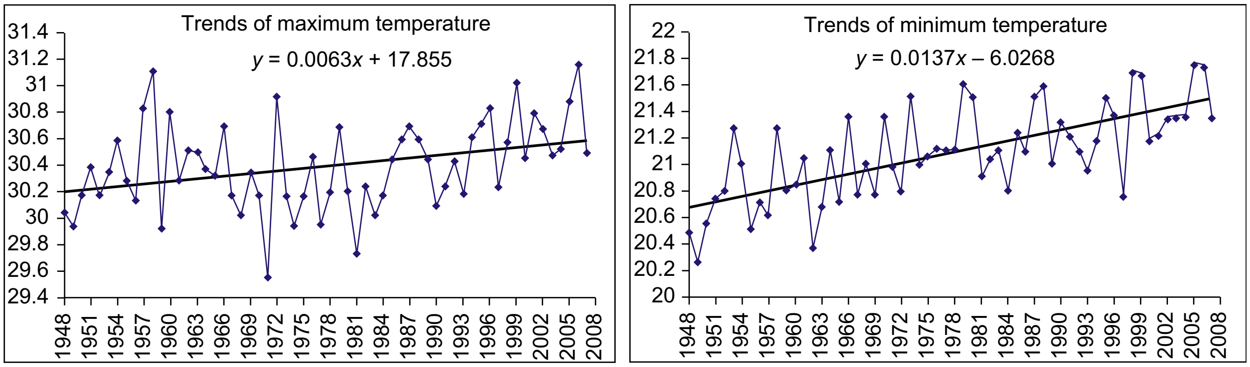


Figure 7 Trends of temperature in Bangladesh based on historical data. CCC, 2009: Characterizing Long-term Changes of Bangladesh Climate in Context of Agriculture and Irrigation. Climate Change Cell, DoE, MoEF; Component 4b, CDMP, MoFDM. Month 2009, Dhaka.

Table 4 Mean seasonal temperature trends in Bangladesh

	Trends in Bangladesh mean temperatures (°C per century)	
Season	*1948–2007*	*1980–2007*
Winter (Nov–Feb)	+1.67	+1.33
Summer (Mar–May)	+0.26	+2.15
Monsoon (Jun–Oct)	+1.05	+2.44
Annual (Jan–Dec)	+1.03	+2.14

CCC, 2009: Characterizing Long-term Changes of Bangladesh Climate in Context of Agriculture and Irrigation. Climate Change Cell, DoE, MoEF; Component 4b, CDMP, MoFDM. Month 2009, Dhaka.

separate the anthropogenic and climatic factors that are responsible for such a trend. However, the sequence of development in the Ganges basin gives us some idea of the anthropogenic factors:

1949–59: Initiation of major development works in the Ganges basin but the Ganges basin was still very near to its natural state without significant interventions.
1960–74: Pre-Farakka period from 1960; major storage and diversion projects commissioned.
1975–96: Pre-Ganges Water Treaty (GWT) period from the commissioning of Farakka barrage.
1997–2007: Post-GWT period.

During the period 1949–2005, the mean annual flow volume at Hardinge Bridge on the Ganges River was about 365 458 MCM (million cubic meter) with a range of 201 293–528 518 MCM. The lowest volume of water available was in 1992 and the highest in 1956. The available data indicate a slightly increasing trend of Ganges flow in the 1949–59 period at Hardinge Bridge. As shown in Table 5, during 1960–74 and 1975–96, flow volumes at Hardinge Bridge shows a decreasing trend in both the dry (Nov–Apr) and wet (Jun–Oct) periods. As shown in Figure 8, there is a decreasing trend of flow in both the dry and wet periods observed for the Ganges River at Hardinge Bridge. The ratio between the discharges of the dry and monsoon seasons for the Ganges River is 1:6 (World Bank 2000).

During the period 1960–2005, the mean annual flow volume of the Jamuna River at Bahadurabad was about 640 568 MCM, which varies from 515 392 to 864 023 MCM. The lowest volume of flow was available in 1986 and the highest in 1990. The available data for the Brahmaputra (i.e., Jamuna) at Bahadurabad from 1960 to 2005 indicate that the average dry season flow represents only 16% of the total annual flow (see Table 6). An increasing trend of flow in both dry and wet periods is observed for the Brahmaputra River at Bahadurabad (see Figure 9).

Natural calamities in Bangladesh result in major economic and social impacts and loss of life. The 1998 floods, which inundated two-thirds of Bangladesh, caused a loss of 5.5% of Gross Domestic Product (GDP) (see Table 7). It is interesting to note that the next major flood (in 1998) had a larger return period and more area was affected, but compared to the 1988 flood, less people were affected (and killed), less houses and crops were damaged, and asset losses (as percentage of GDP) were also less. This suggests that warning systems and other lessons learnt were successfully implemented after the 1988 flood. However, the length of roads damaged increases in time,

Table 5 Average volume of the Ganges River at Hardinge Bridge

	Dry average (Nov–May)		*Wet average (Jun–Oct)*		*Yearly average*	
Period	*Volume (MCM)*	*% Change from previous period*	*Volume (MCM)*	*% Change from previous period*	*Volume (MCM)*	*% Change from previous period*
1949–59	62 916		327 013		396 173	
1960–74	57 559	–9	304 248	–7	374 382	–6
1975–96	34 141	–41	299 056	–2	336 764	–10
1997–2005	42 474	24	340 773	14	387 630	15

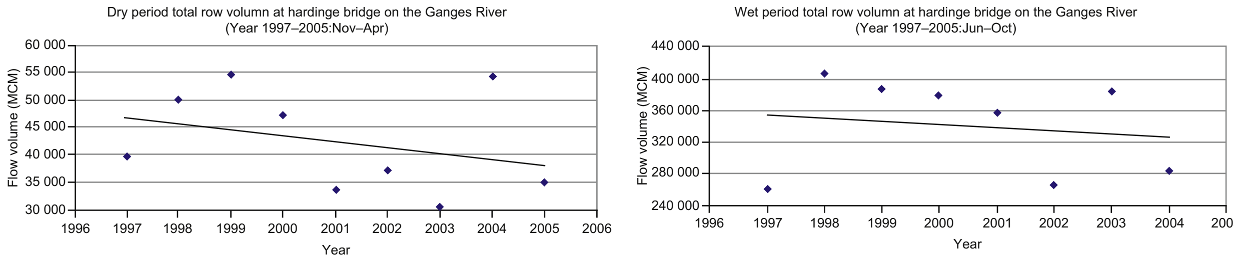


Figure 8 Dry (left) and wet (right) period flow variation at Hardinge Bridge on the Ganges River.

Table 6 Average volumes of the Brahamaputra River at Bahadurabad

	Dry average (Nov–May)		*Wet average (Jun–Oct)*		*Yearly average*	
Period	*Volume (MCM)*	*% Change from previous period*	*Volume (MCM)*	*% Change from previous period*	*Volume (MCM)*	*% Change from previous period*
1957–66	139 568		476 988		616 556	
1967–76	135 468	–3	467 220	–2	602 688	–2
1977–86	143 470	6	465 639	0	609 109	1
1987–96	172 778	20	546 910	17	719 688	18
1997–2006	150 578	–13	464 072	–15	614 650	–15

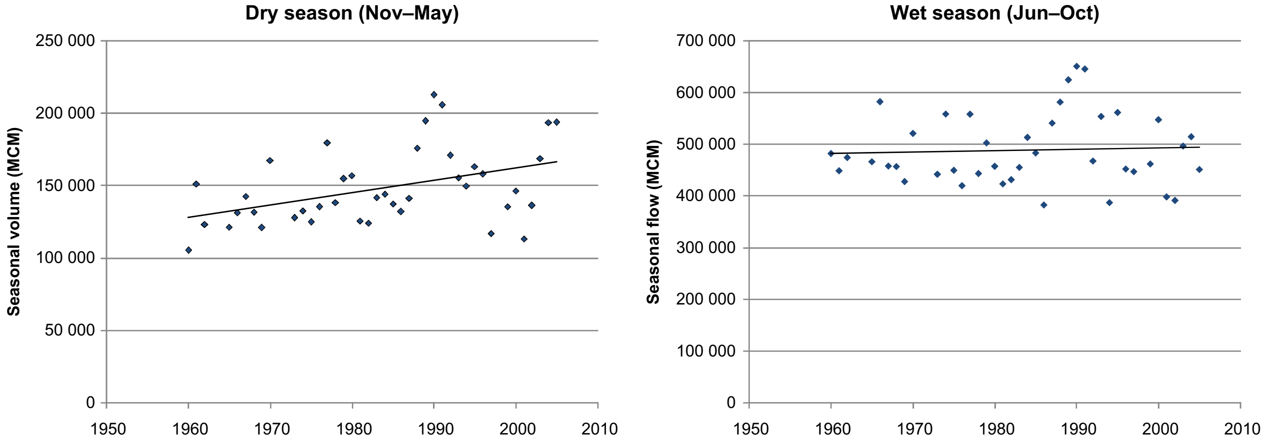


Figure 9 Dry (left) and wet (right) period flow variation at Bahadurabad on the Brahmaputra River.

Table 7 Losses from recent floods

Impact	*1974*	*1987*	*1988*	*1998*	*2004*	*2007*
Area affected (thousand sq km)	53	57	90	100	56	62
% Total land area inundated	37	40	63	69	39	42
Millions of people affected	30	30	47	31	33	14
Fatalities (number)	28 700	1657	2379	918	285	1110
Houses damaged (thousands)	na	989	2880	2647	895	1000
Roads damaged (km)	na	na	13 000	15 927	27 970	31 523
Crops damaged (millions ha)	na	na	2.12	1.7	1.3	2.1
Asset losses (million US$)	936	1167	1424	2128	1860	1100
GDP (million US$)	12 459	23 969	26 034	44 092	55 900	68 400
Asset losses (% of GDP)	7.5	4.9	5.5	4.8	3.3	1.6
Return period (years)	9	13	55	90	12	14

World Bank, 2011: The Cost of Adapting to Extreme Weather Events in a Changing Climate, Bangladesh Development Series, Paper no. 28, The World Bank, Bangladesh Office. [Available online at www.worldbank.org.bd/bds.]

even for smaller flood events. For example, comparing the impacts of 1998 flood with 2007, one can see that the length of roads damaged almost doubles in 2007 even though it is a considerably smaller flood. In fact, in 2007, the number of fatalities and crops damaged also increased compared to 1998. This was likely due to the increase in population and expansion of agricultural activities: more and more human habitation and farms are located in the floodprone areas because of tremendous pressure on land. As a result, risks to human life and the economy have increased. It is envisaged that the risk will further increase from climatic impacts in terms of increased flooding, waterlogging, storm surge, drought, and salinity intrusion. This makes Bangladesh one of the most vulnerable countries to climatic impacts. The Sidr cyclone of 2007 resulted in a loss of 2.6% of GDP. On average, loss of GDP due to natural calamities ranges between 0.5 and 1% of the country's GDP. However, as shown in Table 7, the percentage of GDP affected due to major floods is decreasing, which suggests that the national economy is becoming more robust to such disasters.

5.24.3.3 Water Demands

In terms of water availability, March is a critical month in the country as irrigation demands are highest and surface flows are very low. Irrigated agriculture is the major water-using sector with rice cultivation being the single most important economy activity. The cropping calendar is based on the temporal distribution of rainfall and temperature throughout the year. In most areas, aus rice is the premonsoon crop; aman is the monsoon rice; and boro rice is grown in the dry season with irrigation. Aman is generally the main rice crop occupying the area, followed by boro; and then aus. Aus rice has reduced in importance after the introduction of high yielding varieties of boro rice. This continues to have a major impact on water resources, as the demand for water from agriculture in the dry season has been increasing. In the future, agricultural demand for water is likely to increase due to further irrigation expansion. It has been estimated that irrigated area may increase to about 7 million ha by 2020 (World Bank 1998). This would be a critical change in water demand.

Although, at present, irrigated agriculture is the main water user, demand from urban areas is increasing due to overall national population growth (see Table 8). Economic growth is also leading to increases in industrial water demands. It is likely that the water supply for domestic and industrial usage will require a reduction in groundwater irrigation in many areas. The National Water Policy gives the agriculture sector a relatively low priority and sets the following order for water usage: domestic and municipal uses, nonconsumptive uses (e.g., navigation, fisheries, and wildlife), river regime sustenance, and other consumptive and nonconsumptive uses including irrigation, industry, environment, salinity management, and recreation (WARPO 2001). The shift of water use away from agriculture could be a critical positive change in water demands, as this could free up vital resources in certain areas.

Table 8 Estimated population growth

Year	*National Population (million)*
1991	111
2000	131
2010	150
2020	170
2025	176

Data from Ahmad, Q. K., A. K. Biswas, R. Rangachari, and M. M. Sainju, Eds., 2001. *Ganges–Brahmaputra–Meghna Region: A Framework for Sustainable Development.* University Press Limited, Dhaka, Bangladesh.

5.24.3.4 Water Policies, Plans, etc.

Several key laws, policies, and plans directly related to water resources have been developed since the mid-1990s: Environment Conservation Act (1995), National Environment Management Action Plan (1995), National Policy for Safe Water Supply and Sanitation (1998), National Fisheries Policy (1998), National Water Policy (1999), National Water Management Plan (2004), and National Arsenic Mitigation Policy (2004).

There have also been many laws, policies, and plans that are indirectly related to water resources: National Environment Policy (1992), National Environment Action Plan (1992), National Agriculture Policy (1994), National Forest Policy (1994), National Energy Policy (1996), Forestry Master Plan (1993–2012), Sustainable Environment Management Program (1997), and National Conservation Strategy (2005).

The National Water Management Plan (NWMP) (2004) provides a framework for 24 line agencies and other organizations to plan and implement their activities in a coordinated manner. The NWMP is a rolling plan to be reviewed and updated every 5 years. However, a formal review has not yet been conducted. This highlights the difficult problem of updating and implementing well-meaning policies, plans, and laws. This results in continuing deterioration of the water resources around the country.

There have been many major water engineering projects implemented throughout the country, e.g., flood control and drainage projects. The cumulative effects of these human interventions have had major impacts on the country's water resources. The BWDB is responsible for the planning and execution of over 400 projects related to flood control, drainage, irrigation, coastal protection, and erosion control. Major investments in the water sector are made by the Ministry of Water Resources through the BWDB. For example, the BWDB is undertaking a feasibility study and detailed engineering design for constructing a barrage on the Ganges River (Government of Bangladesh 2005). The BWDB also plays a vital role in collecting hydro-meteorological data from its numerous measuring stations around the country.

Relatively smaller scale projects are executed by the LGED. Another major executing agency is the DPHE, which is responsible for managing projects related to water supply and sanitation in rural areas and towns. Currently, DPHE is developing water supply and sanitation master plans for 148 towns around the country. In city areas, there are water supply and sanitation companies mandated to service metropolitan areas.

This includes abstraction and treatment of water from surface and groundwater sources and also treatment and discharge of wastewater.

Quite often it is found that structures built to control floods in one area have aggravated the problems in others and hampered agriculture, fishing, and navigation activities. Given the differential needs of the various water management issues, improved coordination of the activities of relevant agencies will lead to better plans and projects.

5.24.3.5 Contamination

Critical changes in contamination include variations in urban pollution levels and salinity intrusion in coastal areas. Urban pollution impacts water resources mainly during the dry season and in localized areas. Laws, policies, and plans are already in place to limit this threat to water resources (as discussed in the previous section).

Recent measured data (2005–09) have shown a clear increasing trend in river salinity in the southwest region (see Figure 10). Around 15 500 km^2 of coastal area experiences salinity in excess of 1 ppt in the surface water during April and May every year. The extent of salinity in the groundwater system could not yet be quantified, but it is understood from data from different sources that out of 19 coastal districts, 50% have salinity above 1 ppt at various aquifer units. No sufficient data exist to exactly identify the cause of such increasing trends, but it is widely assumed that freshwater withdrawal in the upstream has probably caused the increase in salinity over the years.

In the future, another reason for increased river salinity could be due to SLR. The salinity model of Bangladesh built by Institute of Water Modeling (IWM) has projected significant impact on salinity intrusion in the coastal region of Bangladesh. Due to an SLR of 60 cm, the saline front could intrude a maximum of around 55 km inland. For an additional 60 cm rise in sea level, the saline front would further propagate 40 km (Figures 11 and 12). This may cause major havoc in the coastal economic and ecological systems.

An increase in river salinity has major implications to the water supply, soil salinization, aquifer salinization, and ecosystem. It is likely that sea level rise and increase in storm surges will exacerbate the situation in the future.

5.24.4 Impacts of Critical Changes and Actions to Eliminate Negative Impacts

The main critical changes to water resources in the country are listed in Table 9. In order to further prioritize these critical changes, a simple risk assessment method has been used by the authors. The risk has been assessed for each critical change based on its potential impact on water resources and also its likelihood. A risk score is calculated by multiplying the impact score with the likelihood score. The impact and likelihood scores have been provided by the authors based on experience in the water resources field.

After highlighting some key sectoral impacts of the above critical changes in water resources, a discussion of some of the main adaptations that have been adopted is provided. In general, in Bangladesh adaptation is undertaken at a local scale and, in fact, has adopted a very bottom-up contextual approach since the 1960s.

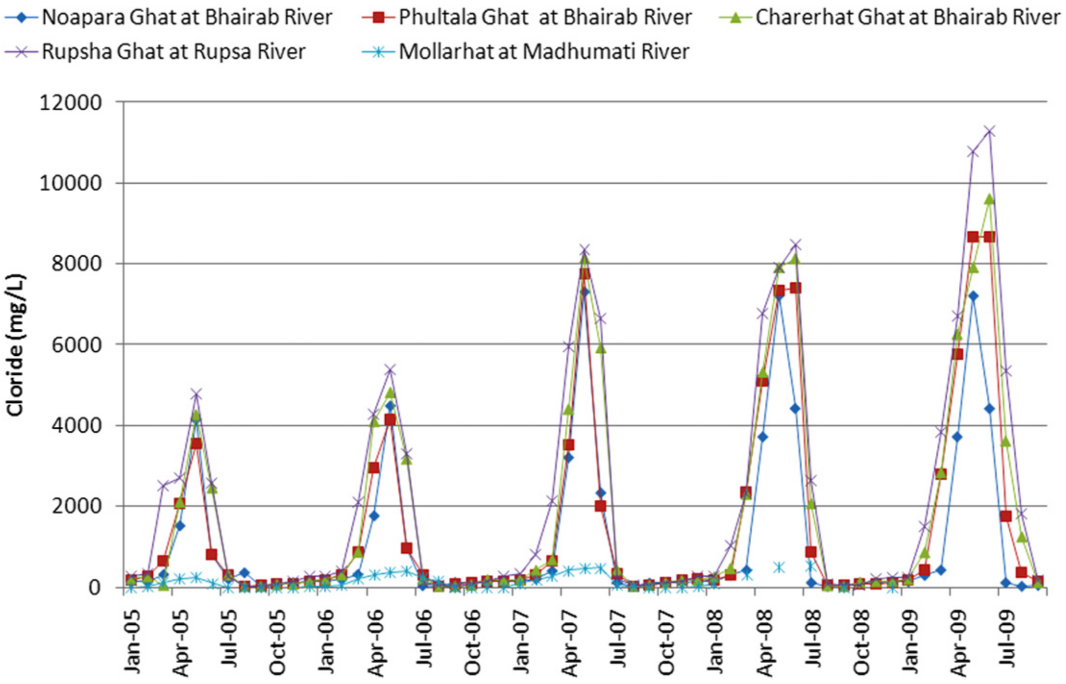
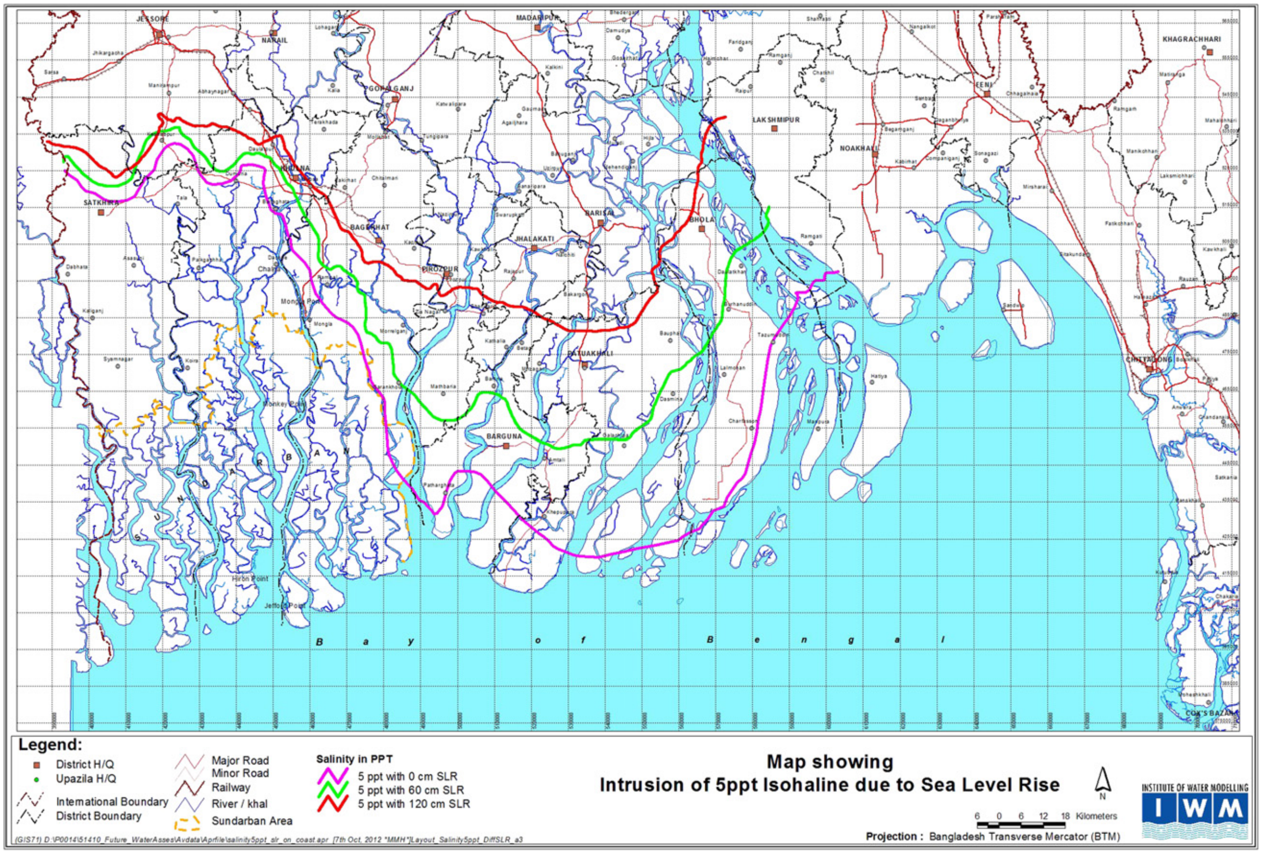


Figure 10 Chloride concentration at five locations in the southwest region from 2005 to 2009. DoE 2010.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BHOLA
PIROZPUR
PATUAKHALI
BARGUNA
CHITTAGONG
COX'S BAZAR
Hiron Point
Jefford Point
B a y o f B e n g a l
Legend:
District H/Q
Upazila H/Q
International Boundary
District Boundary
Major Road
Minor Road
Railway
River / khal
Sundarban Area
Salinity in PPT
5 ppt with 0 cm SLR
5 ppt with 60 cm SLR
5 ppt with 120 cm SLR
Map showing
Intrusion of 5ppt Isohaline due to Sea Level Rise
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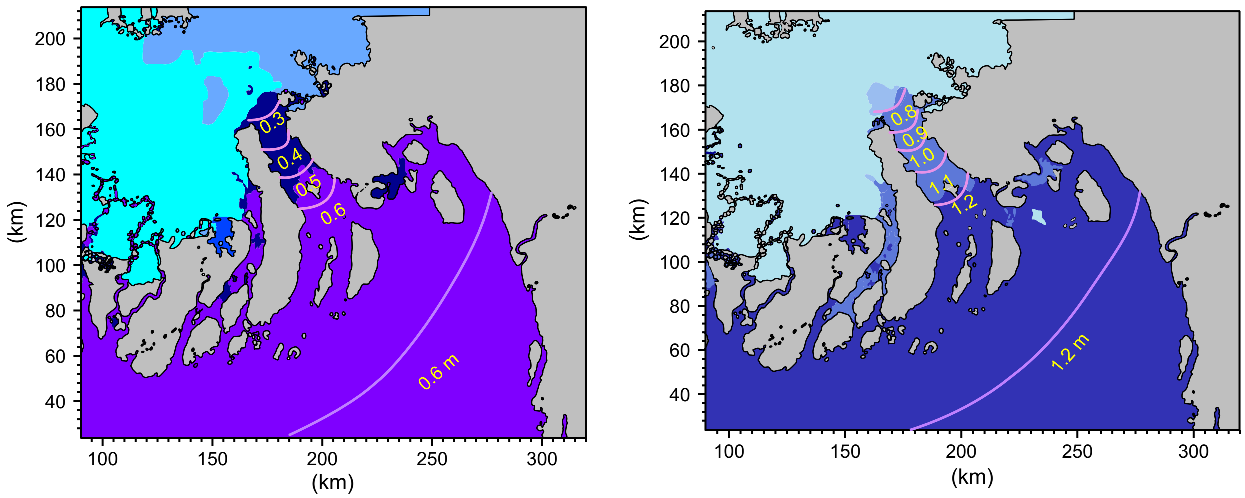
Projection : Bangladesh Transverse Mercator (BTM)
INSTITUTE OF WATER MODELLING
IWM

Figure 11 Salinity intrusion in the coastal region of Bangladesh.


200
180
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140
120
100
80
60
40
(km)
100
150
200
250
300
(km)
0.3
0.4
0.5
0.6
0.6 m
0.8
0.9
1.0
1.1
1.2
1.2 m

Figure 12 SLR of 60 cm (left) and 120 cm (right).

5.24.4.1 Sectoral Impacts

The consequences of changes in the water regimes on other economic and biophysical sectors are often nonlinear, complex, and difficult to distil from anthropogenic influences. During the last decade, comprehensive research, studies, information, and tools on climate and its impacts have become available and understanding of the processes, pathways, and consequences has improved. Different studies show that in Bangladesh the sectors that are predicted to be the most affected by changes in water and water resources are agriculture, health, fisheries, biodiversity, and infrastructure. The impacts of climate on different sectors and systems through water are listed in Table 10.

Table 9 Summary of key risks to water resources

Variable	*Critical change*	*Impact on water resources*	*Likelihood*	*Risk score (impact × likelihood)*
Climate and weather	Timing of monsoon	3	2	6
Climate and weather	Increased rainfall intensity	3	3	9
Climate and weather	Increased temperatures	2	3	6
Transboundary flows	Ganges flow decrease	3	2	6
Transboundary flows	Ganges flow increase	3	2	6
Transboundary flows	Brahmaputra flow decrease	3	1	3
Transboundary flows	Brahmaputra flow increase	3	3	9
Transboundary flows	Meghna flow decrease	3	2	6
Transboundary flows	Meghna flow increase	2	2	4
Water demands increase	Agricultural demands	3	2	6
Water demands increase	Urban demands	2	3	6
Water policies, plans, etc.	Poor implementation	3	2	6
Contamination	Increase in river salinity	3	3	9
Contamination	Increased urban pollution	2	2	4

Score definitions–impact: 3 = major, 2 = moderate, 1 = minor; likelihood: 3 = very likely, 2 = possible, 1 = small chance; risk: <3 = low, 3–4 = medium, ≥ 6 = high.

The people of Bangladesh have adapted to the risk of floods, droughts, and cyclones over the generations. In Bangladesh water resources management systems have focused on the need to regulate and distribute water for irrigation, food production, and water supply, and flood defense and drainage measures were taken to reduce flooding damage. But increased pressures on water resources from high population density, poor infrastructure, and low resilience to economic losses are now compounded by uncertainties of climate variability. This means the present approaches and traditional methods of water resources management systems need to be reassessed. New approaches, knowledge, and technology need to be considered for improved adaptation to climate variability.

Over the last 50 years, major investment has been made to reduce the climate-related vulnerability of people and economic resources in Bangladesh. These include both structural and nonstructural measures. Around 1.75 million ha land in the coastal areas has been empoldered (155 polders) to protect the area from salinity intrusion and tidal inundation. More than 5000 cyclone and flood shelters have been constructed. Around 4 million ha have been brought under flood management schemes (266 schemes). Most of the major roads and highways have been raised above flood levels. A very comprehensive disaster management and flood warning system covers all of Bangladesh (DMB 2010). Climate resilient varieties of rice and other crops have also been developed. These measures have surely made Bangladesh more resilient of climate-related hazards, but more still needs to be done in view of the expected climate variability impacts and sea level rise.

5.24.4.2 Flood Management

Since ancient times, life in Bangladesh has been centered on the numerous rivers, the annual cycles of flooding, and the hydrological characteristics of the country. The modern period efforts for flood management public initiatives began in 1957, with the appointment of the Krug Mission in the wake of the devastating floods in 1954, 1955, and 1956. At the request of the then Government of Pakistan, the United Nations sent this technical assistance mission, which emphasized the need for flood control to increase agricultural production. The East Pakistan Water and Power Development Authority, now known as Bangladesh Water Development Board, was created in 1959 and was responsible for the planning, design, operation, and management of all water development schemes. Consequently, a Master Plan for water development formulated in 1964 included a portfolio of 58 land and water development projects for implementation spread over 20 years. On the basis of this plan, large-scale land and water development schemes were initiated by the government (Datta 1999).

In 1972, the Land and Water Sector Study, on the other hand, emphasized agricultural production rather than flood control and underlined the need for considering land and water as integrated resources. Recommendations included the development of minor irrigation through low lift pumps and tube wells supported by complementary less capital and labor intensive FCD projects.

Embankment construction has been the major activity in these FCD projects as part of the comprehensive flood and land management strategy. Embankments of a total length of more than 8300 km have been constructed since 1959 in the country. Flood protection for major cities, important commercial and industrial areas, and key transport and communication infrastructure are given the highest priority. This is reflected in the design of the embankments surrounding the four major cities, Dhaka, Chittagong, Khulna, and Rajshahi urban areas. A 100-year flood frequency was adopted as the design water level for urban settlements, whereas the embankments protecting agricultural areas are normally designed for a flood of 25-year frequency.

Over the past three decades, flood, considerable change, and progress based on practical experience and lessons learned can be seen in the planning and implementation of these projects. Emphasis is on a more comprehensive approach with multiobjective and multisectoral planning, rather than single-objective (e.g., food grain self-sufficiency) planning. The generally better performance of small-scale interventions and private sector development has seen reduced importance of large scale government projects. Stakeholder participation and consultation at all levels and from the private and Non-governmental Organization (NGO)

Table 10 Examples of major impacts by sector mainly through water resources

Variable	*Water resources*	*Agriculture*	*Health*	*Biodiversity*	*Industry and infrastructure*
Increased temperature (warmer and humid weather)	Increased water temperatures Increase in evaporation Earlier snow melting Increased algae growth reducing dissolved oxygen levels in water body Changes in mixing patterns and self-purification capacity of water bodies	Less water available for agriculture, more irrigation needed Changes in crop productivity Changes in growing season	Changes in vector-borne diseases Increase of fatalities due to heat waves, and decreased personal productivity Increased risk of respiratory and skin diseases	Changes in species composition, organism abundance, productivity and phenological shifts, for example, earlier fish migration Eutrophication and loss of fish	Degradation of freshwater quality
Increase in heavy precipitation events and more erratic behavior	Flooding Drainage congestion Higher river flows	Damage to crops Soil erosion Inability to cultivate land due to waterlogging of soils	Increased risk of deaths, physical injuries and infections, respiratory and skin diseases Risk of psychological disorders	Damage to habitat Additional flooding adversely affecting vegetation	Disruption of settlements, commerce, transport, and societies due to flooding and migration Pressures on urban and rural infrastructures Loss of property
Higher variability of precipitation including increased droughts	Changes in runoff More widespread water stress Increased water pollution due to lower dissolution of sediments, nutrients, dissolved organic carbon, pathogens, pesticides and salt, as well as thermal pollution	Land degradation Lower yields/crop damage and failure Increased livestock deaths	Increased risk of food and water shortage Increased risk of malnutrition Increased risk of waterborne and food-borne diseases	Water stress will damage habitat and ecosystems (e.g., forest ecosystems in Madhopur and Barind Tract) Causing decline in fisheries stock	Water shortages for settlements, industry, and societies Reduced hydropower generation potentials Potential for population migration
SLR	Salinity intrusion (more areas affected, longer duration of saline intrusion, and higher concentration) Drainage congestion Coastal erosion	Less freshwater available for agriculture and livestock Inability to cultivate land due to waterlogging of soils Loss of agricultural land	Changes in vector-borne diseases Increased heart diseases especially in pregnant women	Loss of habitat for freshwater species	Degradation of freshwater quality for settlements, industry, and societies
Increased frequency and severity of cyclones and storms	Higher storm surges Salinization of water bodies and aquifers	Damage to crops and livestock	Increased risk of malnutrition Increased risk of waterborne diseases	Damage to habitat, vegetation, and animals	Disruption of settlements, commerce, transport, and societies due to flooding and migration Loss of property

Adapted from UNECE, 2009: Convention on the Protection and Use of Transboundary Watercourses and International Lakes. Guidance on Water and Adaptation to Climate change, United Nations Economic Commission for Europe; MoEF, 2009: Bangladesh Climate Change Strategy and Action Plan 2009. Ministry of Environment and Forests, Government of the People's Republic of Bangladesh, Dhaka, Bangladesh.

sectors as well as the public sector are now recognized to be essential (WARPO 2001). Low-cost activities, such as structural flood proofing and nonstructural measures, are now advocated for rural areas, which are not of high economic importance with urban FCD, are now being given more emphasis than in the past. Present integrated water and land use planning is set to focus on the development of floodplain zoning to accommodate necessary engineering measures and allocate space for habitation patterns, economic activities, and environmental resources.

5.24.4.3 Recent Water Policies, Plans, etc.

The Bangladesh government is very much concerned about climate risks, and this is reflected in several policies that relate to climate variability and water resources management. Bangladesh has a National Adaptation Program of Action (NAPA) (MoEF 2005) and the Bangladesh Climate Change Strategy and Action Plan (BCCSAP) (MoEF 2008, 2009). The NAPA was prepared through a series of national and subnational workshops. It lists 15 adaptation strategies, with water sector related measures such as (MoEF 2005):

- Providing drinking water to coastal communities affected by saline intrusion
- Capacity building for integrating climate variability in planning, designing of infrastructure, conflict management, and land–water zoning for water management institutions
- Information dissemination on climate variability and adaptation to vulnerable communities for emergency preparedness measures and raising awareness on climatic disasters
- Construction of flood shelters and an information and assistance center to cope with recurrent floods in major floodplains
- Mainstreaming adaptation of climate variability into policies and programs in different sectors (focusing on disaster management)

The NAPA is an integral part of national development policies, plans, and programs. The BCCSAP (MoEF 2009) builds on the NAPA and it guides actions in all areas related to climate variability. The strategy contains 44 programs formulated around six pillars: (a) food security, social protection, and health, (b) comprehensive disaster management, (c) infrastructure, (d) research and knowledge management, (e) mitigation and low carbon development, and (f) capacity building and institutional strengthening. The BCCSAP has been developed by the Government of Bangladesh in consultation with civil society, including NGOs, research organizations, and the private sector.

The Coastal Zone Policy (2005) provides general guidance for the management and development of the coastal zone in a manner so that coastal residents are able to pursue their life and livelihoods within a secure and conducive environment. The Integrated Coastal Zone Management Program (2004) identified critical impacts of climate variability and SLR, such as increased drainage congestion, reduced freshwater availability, disturbance of morphological processes, and increased intensity of extreme events and disasters.

Bangladesh has also motivated neighboring countries to actively seek adaptation options to climate variability at the regional level. This is reflected in the Sixteenth South Asian Association for Regional Cooperation summit held in Thimphu, Bhutan, in April 2010. The Thimphu statement on climate gives high priority toward preserving and sustainably managing the rich, fragile, and diverse ecosystems of South Asia and expresses deep concern about the adverse effects of climate and its impact on the region (SAARC 2010).

Other policies addressing climate variability also include the National Conservation Strategy and the Poverty Reduction Strategy Paper. Also, the Water Supply and Sanitation Sector Development Plan was finalized in 2011. This represents a new approach by the Government to integrate strategies for a sector across various administration levels. Furthermore, the Dhaka Wastewater Master Plan will be finalized in 2012, which, if successfully implemented, can lead to a major improvement in the quality of the capital's peripheral rivers.

5.24.4.4 Other Adaptation Measures

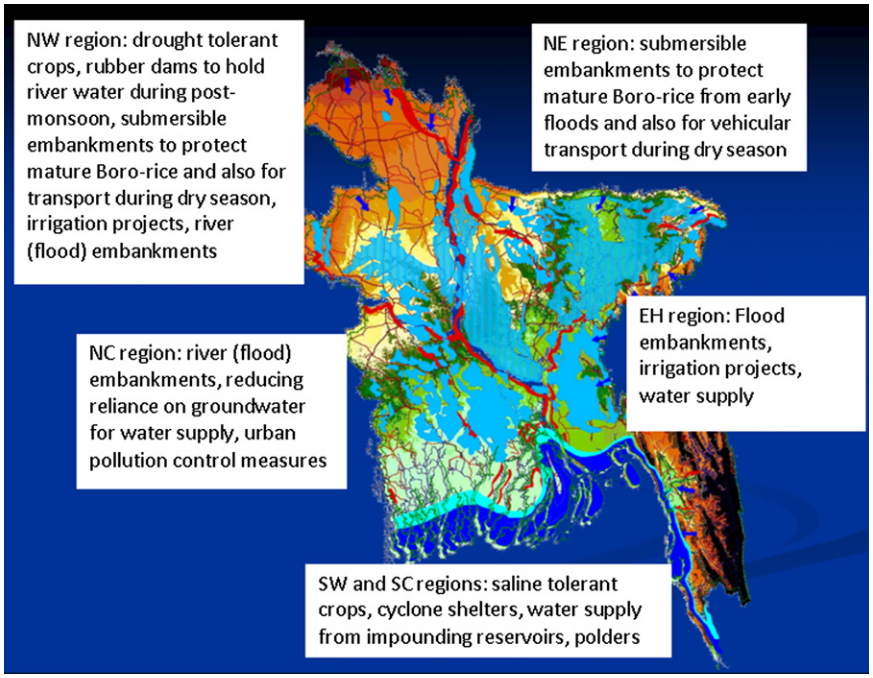
Under various initiatives, adaptation measures against various climate variability impacts have been implemented (see Figure 13).

Over 2000 cyclone shelters have been built to provide refuges for communities from storm surges caused by tropical cyclones and 200 shelters from river floods (MoEF 2009). Additional cyclone and flood shelters need to be constructed due to population increases.

There are ongoing agricultural research programs looking to develop saline, drought, and flood-adapted high yielding varieties of rice and other crops (MoEF 2009), as well as irrigation schemes to enable farmers to grow a dry season rice crop in areas in drought-prone areas (MoEF 2009). There are also flood management schemes to raise the agricultural productivity of many thousands of hectares of low-lying rural areas and to protect them from extremely damaging severe floods (MoEF 2009). Coastal embankment projects, involving over 6000 km of embankments and polder schemes, were designed to raise agricultural productivity in coastal areas by preventing tidal flooding and incursion of saline water (MoEF 2009). Where these polders are not properly designed, increased monsoon intensity can worsen internal waterlogging/drainage problems. This could be a potential example of 'mal-adaptation' (i.e., bad adaptation or adaptation gone wrong). Polder embankments also need to be redesigned to deal with storm surges with SLR. Storm surge modeling will help target adaptation efforts, surge forecasting, and disaster preparedness.

Some coastal regions, including polder areas, suffer from drainage congestion problems. This problem is likely to worsen with increased SLR. Tidal dredging is an innovative method that can help adaptation to increase capacity of coastal drainage channels and thus reduce the impact of SLR on drainage congestion in coastal areas. Redesign of drainage infrastructure will also be required. In critical locations pumping needs to be considered.

Recently, comprehensive disaster management projects, involving community-based programs and early warning systems for floods and cyclones, have been implemented (MoEF 2009). There are also specific programs for implementing drinking water and sanitation projects in areas at risk from climate variability (e.g., coastal areas, flood- and drought-prone areas) (MoEF 2009).



NW region: drought tolerant crops, rubber dams to hold river water during post-monsoon, submersible embankments to protect mature Boro-rice and also for transport during dry season, irrigation projects, river (flood) embankments

NE region: submersible embankments to protect mature Boro-rice from early floods and also for vehicular transport during dry season

EH region: Flood embankments, irrigation projects, water supply

NC region: river (flood) embankments, reducing reliance on groundwater for water supply, urban pollution control measures

SW and SC regions: saline tolerant crops, cyclone shelters, water supply from impounding reservoirs, polders

Figure 13 Location and main adaptation measures in Bangladesh.

Through technical support from organizations such as IWM, Center for Environmental and Geographic Information systems, and Institute of Water and Flood Management, there is better integrated water resources management, where conjunctive use (water from surface and ground sources) is properly implemented and also proper planning is undertaken with the use of sound information and reliable decision-making tools.

5.24.5 Specific Recommendations for Policymakers and Stakeholders

In this chapter, we have presented a contextual, bottom-up approach, for identifying and prioritizing adaptation measures. In this regard, it is important that adaptation strategies are cognizant of local issues and threats in addition to climate risks (whether from projected model-based risks or otherwise). Water resources play critical roles in Bangladesh's environmental, social, and economical systems. At the same time, the country's water resources are sensitive to natural and socioeconomic variables. In this regard, the key variables are seasonal and long-term climate variability; transboundary flows (surface and groundwater); water demands (increasing trend and changing nature); local to national level policies, programs, and projects; and contamination (from industry and natural sources).

Using a framework based on bottom-up analyses, critical changes in the key variables were identified. The framework took into account temporal and spatial changes in the key natural and socioeconomic variables. Using this approach, it was possible to highlight critical changes in climate and weather patterns, such as monsoon rainfall timing, and increases in temperatures and drought conditions, which have major impacts on agriculture and fisheries sectors – key components of Bangladesh's economy. Apart from climate, the other key threats to water resources in Bangladesh are:

- Population growth (leading to higher water demands)
- Fast economic development (increasing water demands and causing localized pollution problems)
- Changes in upstream flow conditions in transboundary rivers
- Salinity intrusion in coastal rivers

The observed and anticipated change in the climatic drivers will not only disrupt the supply side in terms of freshwater availability considering floods, droughts, sediments, and drainage issues, but also will disturb the demand side in terms of irrigation, fisheries, navigation, and domestic and industrial usage.

From the analysis of existing water sector policies and plans, in relation to possible adverse impacts of climate variability, there needs to be more effective mechanisms to deal with climatic change. Policy reform to tackle climatic concerns can evolve from an increased understanding of climate variability processes, mitigation, and adaptation options. Again, experience from case studies in other countries might be useful for policy directions.

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5.25 Water Resources Vulnerability in the Context of Rapid Urbanization of Dhaka City (a South Asian Megacity)

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5.25.1 Introduction

On 28 July 2009, a storm system spanning an area of about 3000 km^2 over the central region of Bangladesh resulted in a very heavy downpour. In just 6 h, Dhaka city, the capital of Bangladesh (**Figure 1(a)**), received about 448 mm of rain. In a city where urban planning, drainage, and natural wetland storage have been compromized by rapid urbanization, such a massive downpour resulted in catastrophic inundation of the city in a matter of hours (The Daily Mail 2009; **Figure 2**). Precipitation records maintained by the Bangladesh Meteorological Department (BMD) and the Bangladesh Water Development Board (BWDB) indicated that a 53-year record had been broken. The previous record was 326 mm on 13 July 1956 (SPARRSO 2010). Hereafter, the term rainfall is used as shorthand for precipitation.

Although the 28 July 2009 event occurred because of a combination of a monsoonal front and a depression in the Bay of Bengal (SPARRSO 2010), recent records of comparable-magnitude events appeared to have occurred exclusively near large cities (341 mm of rain in 24 h on 14 September 2004 in Dhaka and 425 mm of rain in 24 h on 11 June 2007 in the second largest city, Chittagong). Given that Bangladesh has a fairly comprehensive monitoring network of rainfall across the largely rural and agricultural country (254 daily recording stations since 1950; **Figure 3**), the possibility of land use change (such as urbanization) having played a role in precipitation, runoff generation, and groundwater recharge modification deserves a careful look. For a historical trend of land use change since the beginning of Dhaka City in AD 1600, the reader is referred to the left panel of **Figure 1(b)**. A question that has never been asked by water policy planners and scientists alike is *Does the urbanization of Dhaka city over the past 20 years in a largely rural–agricultural surrounding have any detectable effect on local and regional precipitation and runoff patterns?*

The above question is timely for a number of reasons. Dhaka is the fastest growing megacity in the world with an urban population now close to 14 million (World Bank 2010).

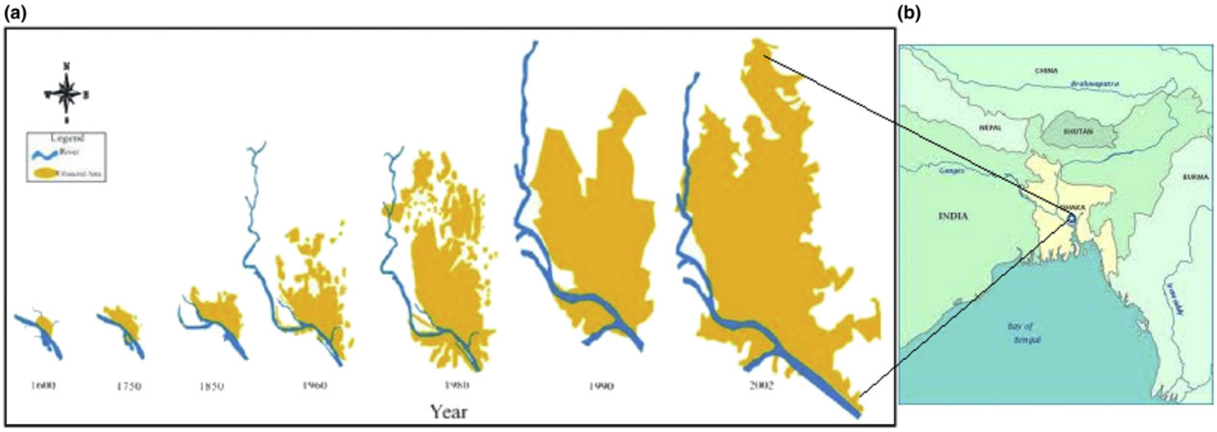

Figure 1 (a) Dhaka city growth since AD 1600 and (b) location of Dhaka in Bangladesh.

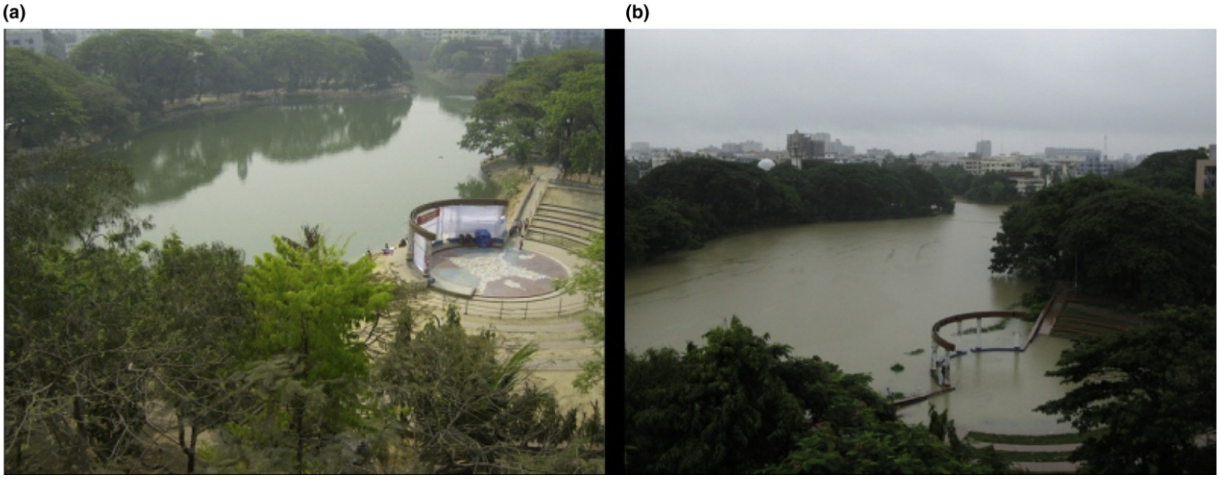

Figure 2 The flooding impact of the 28 July 2009 storm in Dhaka city. (a) Dhanmondi Lake located near a Dhaka suburb during March 2009 (dry season) and (b) 12 h after the storm on 28 July 2009 ended. Source: Sébastien Rist and Aude leroux-Lévesque at http://bideshifilms.com.

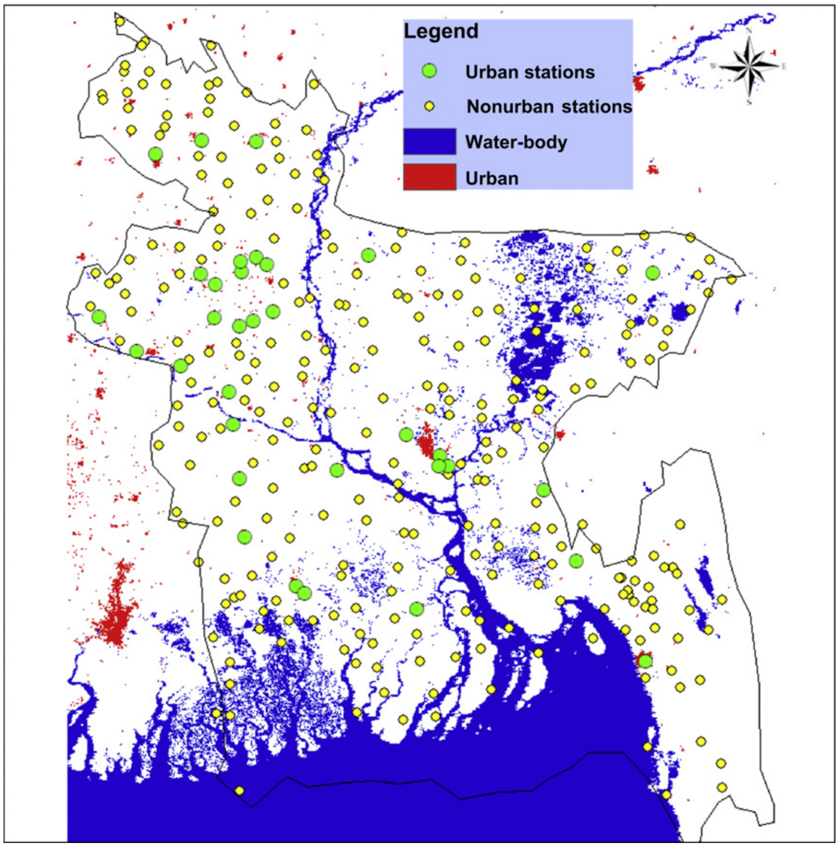

Figure 3 Location of the 254 daily recording rainfall stations from the BMD and BWDB network. Colors green and yellow classify stations as 'urban' and 'nonurban,' respectively, according to MODIS land use classification data.

By 2015, the United Nations (UN) predicts that Dhaka's population will exceed that of Mexico City, Beijing, or Shanghai (Table 1; United Nations 2001). Such a growth rate adds tremendous pressures on the city's renewable but finite water resources for domestic consumption. With ground water table decreasing at the rate of 2–3 m year^{-1} (Rahman and Hossain 2008) and the recharge zone of the deep aquifers of Dhaka (that supply 80% of the city's safe drinking water) becoming progressively encroached, sustainable water resources development is already a challenging task. The encroachment of pervious area or natural wetlands by unplanned urbanization can be appreciated in Figure 4, in which two LANDSAT images

Table 1 Population and growth rate of some of Asian megacities (UN, 2001)

Megacity	*Population (millions)*	*Annual growth rate (2005–2015) (%)*
Dhaka, Bangladesh	12.6	3.2
Shanghai, China	12.7	1.1
Calcutta, India	14.3	2.0
Jakarta, Indonesia	13.2	2.7
Delhi, India	15.3	2.2
Mumbai, India	18.3	2.2

taken a decade apart show drastic changes in the spatial extent of natural water bodies. The large-scale arsenic contamination of shallow but the more abundant ground water available in the rest of the country (Hossain and Sivakumar 2006) makes the dependence on a single source of water (such as the deep aquifers of Dhaka) a risky option for the future. Other sources, such as surface water resources, therefore need to be explored. It is for this reason that the Bangladesh Government has recently started to explore the viability of withdrawing the polluted river waters around Dhaka city as a mitigating source for the dwindling supply of ground water (Rahman and Hossain 2008).

If surface water is to be assessed of its future potential, the impact of changing trends on rainfall and runoff generation (owing to rainfall partitioning and land use patterns) needs to be understood. Climate projections according to the Intergovernmental Panel on Climate Change (IPCC) Fourth Assessment Report (AR4) indicate that the humid regions of South Asia would be significantly altered in terms of rainfall patterns later in the century (Schneider et al. 2007). If such climate projection is to be believed, then the long-term planning for adaptation must consider the local-to-regional feedbacks between the atmosphere and urbanizing land surface. Such a more 'local' approach can be considered more robust as part of the recently coined 'bottom-up vulnerability' assessment approach of a resource in a changing climate (Pielke et al. 2011). In line with previous arguments articulated by Pielke et al. (2009), this vulnerability concept requires the determination of the climatic threats to a resource (such as water), as well as from other socioeconomic and environmental issues. The relative risk from natural and man-made climate variability and longer-term change is then compared with other risks for adopting the optimal mitigation/adaptation strategy. Hossain et al. (2011) argue that the advantage of this bottom-up vulnerability strategy, which must consider the local-to-regional climate feedbacks, is that even if the forecast of water availability because of model projections or other threats were wrong years later, the optimal adaptation strategy identified from multiple threats should have allowed for this error during planning.

Although Bangladesh has an intricate network of rivers, surface water withdrawal from adjacent rivers is not an immediately viable option for Dhaka city because of high levels of industrial pollution from unregulated waste disposal (Kamal et al. 1999). On the other hand, the rainfall and the generated urban runoff (for artificial recharge) around Dhaka city may be a more cost-effective option for water harvesting given the successful experience of more advanced cities faced with perennial water scarcity. For example, the Seletar–Bedok stormwater harvesting scheme in Singapore is an urban runoff capturing system, in which almost one-quarter of the

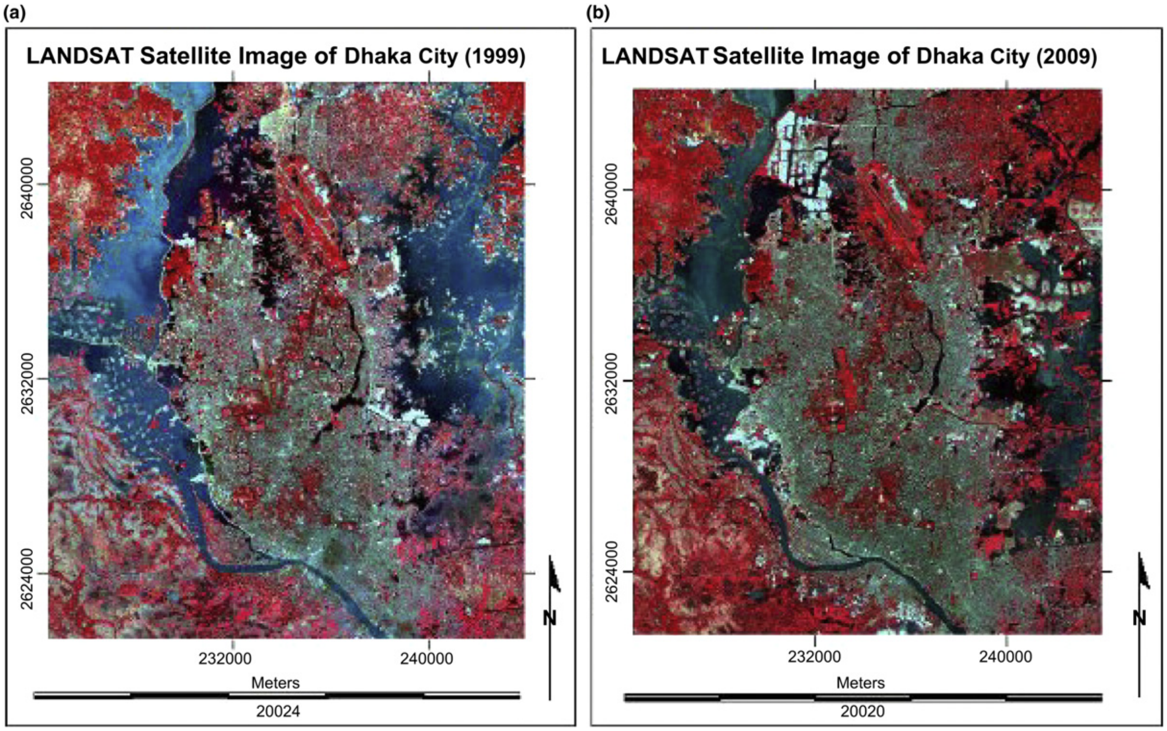

Figure 4 Rapid urbanization and encroachment of pervious area and natural wetlands around Dhaka City as evidenced from LANDSAT images taken during 1999 (a) and 2009 (b).

catchment is in urban area with high rise buildings and impervious surfaces (PUB 2011). The urban runoff generated during storms is directed to a nearby reservoir where it is treated for redistribution through Singapore's drinking water network. If the sustainability of such an urban runoff/rainfall harvesting system is to be explored, rainfall and runoff patterns around Dhaka city needs to be identified in the context of rapid land use change.

There is now considerable evidence suggesting that urbanization can modify rainfall patterns due to a combination of factors (see Mahmood et al. (2009); Shepherd et al. (2010a) for comprehensive reviews), such as (1) increase in cloud condensation nuclei (CCN) concentrations (Ashworth 1929; Rosenfield et al. 2008), (2) changes in surface roughness and low-level convergence (Avissar and Pielke 1989; Shepherd et al. 2010b), or (3) urban heating and land use changes (Bornstein and Lin 2000; Shem and Shepherd 2009). Such changes, independently or synergistically, alter fundamental processes associated with precipitation formation or enhancement (i.e., sensible and latent heat fluxes, convergent flow, cloud water development, and direct thermal circulation patterns).

For example, observational evidence spanning a decade of rainfall measurements indicates that rapid urbanization in the Pearl River Delta of China has reduced precipitation (Kaufmann et al. 2007). However, this study only included urban land cover and no aerosol forcing, which has been shown to suppress precipitation (Rosenfield et al. 2008). A follow-up study reported that the reduction in precipitation was more during the winter season (Seto and Kaufmann 2009). Kishtawal et al. (2009), in a study over the Indian region, found that the frequency of heavy precipitation had actually increased near areas of urbanization. A very recent series of studies by Mitra et al. (2011) has examined changes in premonsoon rainfall in a region near Dhaka city, specifically Kolkata in India. They found evidence that rainfall in the urban observation stations of Kolkata had statistically significant increases over the past 50 or so years, whereas rural stations, the east Gangetic region, and the country itself exhibited no such trends. Lei et al. (2008) found evidence that urbanization in Mumbai, India, contributed to a heavy rainfall event on 26 July 2005. Recent papers by Shem and Shepherd (2009) and Niyogi et al. (2011) have further confirmed that urban land cover can enhance existing convective precipitation systems. Recent studies (such as Molders and Olson 2004; Shem and Shepherd 2009; Shepherd et al. 2010a,b; Niyogi et al. 2011) provide a comprehensive review of the literature on the role of urbanization on the rainfall process and establish that such observations are prevalent in many different geographic, climatic, and seasonal regimes. These studies report the considerable debate on the underlying causes and whether urbanization categorically increases or decreases the intensity and frequency of rainfall. However, most studies agree that under the right circumstances, the urbanization signature on rainfall is detectable.

Regardless of urbanization having a direct impact on the ambient meteorological process of rainfall generation, the study of rainfall patterns in an urban setting is important for sustainable water resources planning because of the urban runoff generation potential of heavy storms. For example, Ntelekos et al. (2007) reported a close relationship between major flash flooding and heavy thunderstorms for Baltimore city (USA) where high urban runoff generation potential was found to be the key factor in overwhelming storm drainage systems. In the study of the recent disastrous flood of Atlanta (in Georgia, USA) in September 2009, Shepherd et al. (2011) found some evidence that urban land cover interactions could have influenced the distribution of the heaviest rainfall and consequential high urban flooding around the city. The frequent urban flooding that is expected to become more frequent and flashier with increasing urbanization is rarely viewed as a 'resource' to mitigate water supply shortage. It seems that only the very advanced cities faced with a historical shortage of water have infrastructure in place to treat urban runoff as a 'resource.' For example, in Singapore, there are several urban runoff capturing reservoirs such as the Seletar–Bedok system (alluded earlier) under construction that aim to convert one-third of Singapore's total area as catchment for urban runoff and reuse, thereby reducing its future dependence on neighboring Malaysia for importing water (PUB 2011).

This study is motivated by the need to assess the water resources vulnerability of the Asian megacity of Dhaka in Bangladesh faced with challenges from climate and socioeconomic pressures. Toward this assessment, the study investigates the rainfall patterns and surface runoff generation potential around Dhaka city in the context of rapid urbanization, which can be viewed as a potential forcing for climate (modification of rainfall process in the atmosphere) and hydrology (modification of runoff transformation on the surface). There are three parts to the study: (1) long-term statistical analysis of rainfall in urban and nonurban regions of Bangladesh to understand the baseline behavior of the greater region, (2) dissection of the weather patterns around Dhaka City during the 28 July 2009 storm event, and (3) rainfall runoff simulations to estimate the potential for harvesting urban runoff from rainfall.

5.25.2 Twenty-Year Analysis of Rainfall Patterns in Urban and Nonurban Regions of Bangladesh

Using daily rainfall records from 254 locations in Bangladesh, the first part of this study investigated the statistical difference between the historical patterns in urban and nonurban regions. The station locations pertained to the combined monitoring network of BMD and BWDB and are shown in Figure 3. Land use/land cover data were obtained from Moderate Resolution Imaging Spectroradiometer (MODIS) Land Cover Type product (Friedl et al., 2002). In this case, the 14-class University of Maryland Classification was used. Accordingly, a binary 'urban' and 'nonurban' classification of the Bangladesh land surface was made. The rainfall monitoring stations located inside an urban area were selected as 'urban' stations, whereas the rest of the stations were classified as 'nonurban'. A total of 24 stations were classified as 'urban' and 230 stations as 'nonurban' using the binary MODIS-based land use classification. Rainfall record for each station spanned 20 years from the mid-1980s to the mid-2000s.

Rainfall histograms were created for four categories: urban monsoon, nonurban monsoon, urban all season, and nonurban all season. From these histograms, the percentiles for the mean, 90% (P90), 95% (P95), and 99% (P99) nonexceedance probability were derived for unconditional and conditional cases (Tables 2(a) and 2(b)). The conditional case (considering only the nonzero rainfall data) is expected to remove the effect of long dry spells during winter months that can mask an underlying trend in the extreme percentiles. Because most of the heavy thunderstorms or 'norwesters' occur during the spring season before the onset of the monsoon season (known locally as 'kalbaisakhi') (IMD Report 1941; Weston 1972), conditional analysis was also carried out for the April–June period (Table 2(c)). This analysis is consistent with the rationale of Mitra et al. (2011), who conducted a similar analysis for Kolkata (in India).

The percentile values reported in Tables 2(a)–(c) indicate that, in all cases (monsoon, all season, and spring), nonurban rainfall is statistically larger than urban rainfall. In order to explore a possible impact on occurrence of heavy rain, analysis was also carried out to observe the effect on frequency of rainfall. The analysis was broken down for heavy events that registered more than 20 mm day^{-1} of rain. Figure 5 confirms that on average, in Bangladesh, nonurban regions experience more days of rainfall than urban regions. Overall, observational data indicate a general suppression of all types of rainfall events in terms of both intensity and frequency in urban regions of Bangladesh.

Although the results appear to agree with a similar study carried out by Kaufmann et al. (2007), where they report for the Pearl River Delta that "This reduction may be caused by changes in surface hydrology that extend beyond the urban heat island effect and energy-related aerosol emissions," there a number of unresolved issues to keep in mind for this study. The presence of particulate matter in air of size less than 10 μm that suppress rainfall and are likely to be present in industrializing environments, was not considered by Kaufmann et al. (2007). In Bangladesh, brick kilns, located in close proximity to urban regions, operate from October–April to supply bricks for the construction season. These kilns have been found to be the major contributor of fine particulate matter in the major metropolitan areas of Bangladesh (Guttikunda 2009). On the other hand, Kishtawal et al. (2009), among others, found a strong relationship between urbanization and heavy rain events, where the impact was usually observed 25–100 km downwind. Hence, a more complete analysis, which is beyond the scope of this study, would require clustering rainfall stations as 'urban' based on a 25- to 100-km downwind proximity to a city rather than on land use alone.

Table 2a Statistical summary of rainfall histogram both for urban and nonurban regions for the unconditional case (where rainfall $\geq$ 0.0 mm day^{-1})

	Precipitation (mm day^{-1}) – all days (unconditional)				
	Mean	*Std. Deviation*	*P90*	*P95*	*P99*
Urban (All season)	5.67	17.30	12.75	29.50	78.84
Nonurban (All season)	7.04	20.00	17.54	36.19	91.67
Urban (Monsoon)	11.92	23.78	31.35	51.98	107.92
Nonurban(Monsoon)	14.47	27.18	37.22	60.79	115.50

Table 2b Statistical summary for rainfall percentiles of the urban and nonurban regions for the conditional case (where rainfall $>$ 0.0 mm day^{-1})

	Precipitation (mm day^{-1}): rain days (Conditional)				
	Mean	*Std. deviation*	*P90*	*P95*	*P99*
Urban (monsoon)	21.59	28.55	48.83	71.95	133.33
Nonurban (monsoon)	25.24	31.88	55.49	81.11	154.68
Urban (All season)	20.82	28.00	46.12	68.04	130.24
Nonurban (all season)	24.61	31.06	53.65	77.88	146.05

Table 2c Same as **Table 2b** but for April–June (conditional case)

	Precipitation (mm day^{-1}) (April–June)				
	Mean	*Std. deviation*	*P90*	*P95*	*P99*
Urban	20.55	23.66	43.22	59.25	104.29
Nonurban	24.06	28.17	49.5	69.55	125.00

Another point to consider is the presence of irrigation, which may play a defining role on modifying precipitation patterns. Bangladesh initiated its green revolution for rice production in the late 1970s through massive expansion of groundwater and surface water irrigation schemes in order to allow three major crop growing seasons a year. A study supporting this point was carried out by Lohar and Pal (1995) to understand the effect of irrigation on premonsoonal rainfall over South West Bengal. They concluded that irrigation reduced the low-level moisture and increased soil moisture. They hypothesized that these processes decreased the intensity of sea breeze circulation and related convection. Therefore, the perennially ponded paddy fields may explain to a large extent the statistical difference between the rainfall percentiles for nonurban and urban regions.

5.25.3 Analysis of the 28 July 2009 Storm Event

According to the Bangladesh Space Research and Remote Sensing Organization (SPARRSO) annual report published in 2010, the 28 July 2009 storm had its genesis in the Bay of Bengal. An area of low pressure formed in the Bay of Bengal on 26 July 2009 that gradually transformed to a fully developed low on 27 July. This then intensified into a depression and subsequently moved to Dhaka City along the northeastern direction producing very heavy rainfall over Dhaka and surrounding regions (SPARRSO 2010). To closely scrutinize the makeup of the storm and understand the possible signature of urbanization, atmospheric reanalysis data was derived from the Modern Era Retrospective-Analysis for Research and Applications (MERRA). The surface sensible heat and latent heat and specific humidity were derived at the level of 850 hPa for the date of the storm. The accumulated rainfall for the same date was acquired using the Tropical Rainfall Measuring Mission (TRMM) Multisatellite Precipitation Analysis (TMPA)

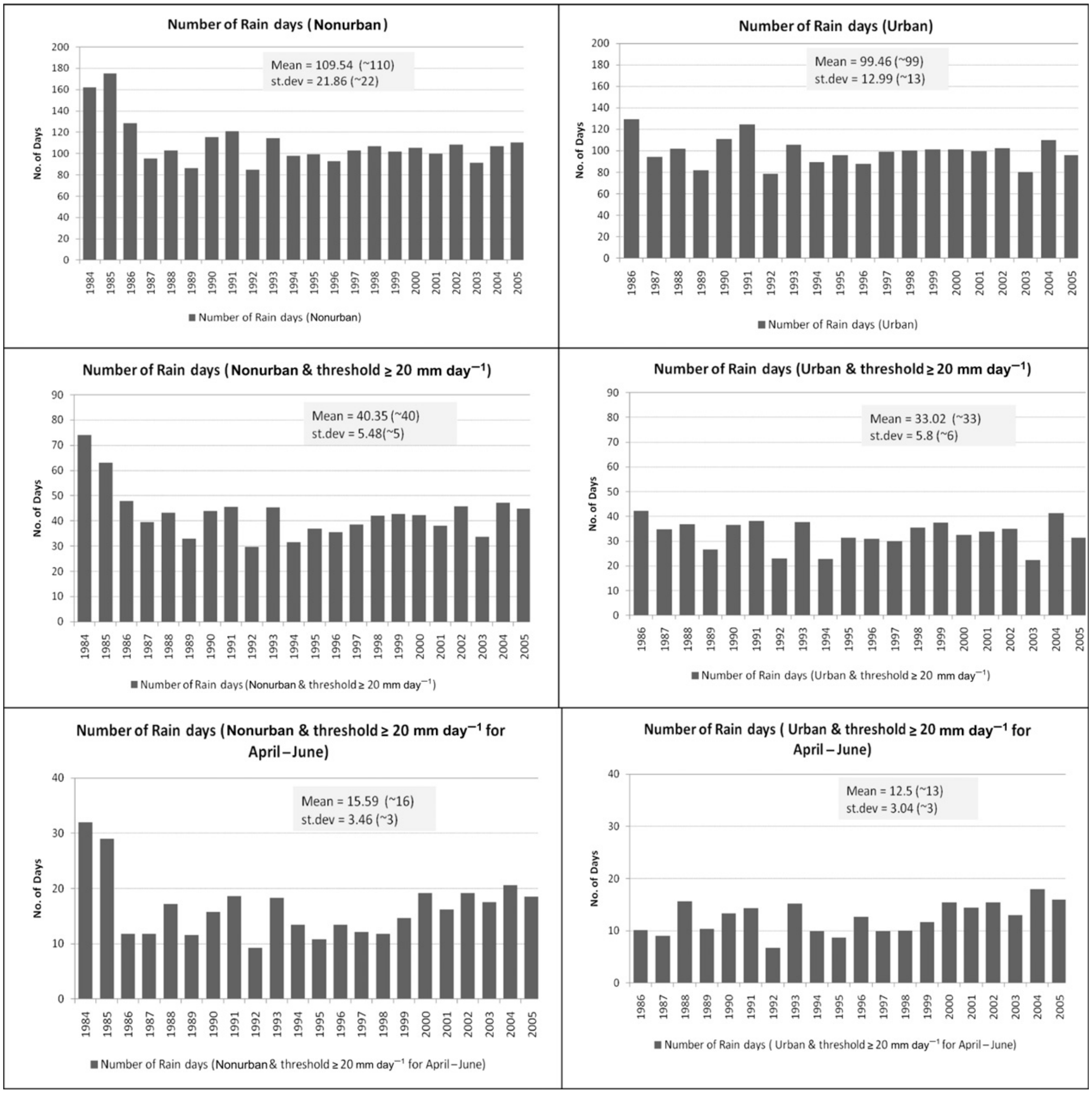

Figure 5 Rainfall frequency analysis for urban and nonurban regions of Bangladesh. Frequency is shown here as the number of rainy days per year for each year. (a) Nonurban and (b) urban. Lowermost panel shows frequency for rain events greater than 20 mm day^{-1}.

(Huffman et al. 2009). The resolution of the data ranged between 0.25 and 1.25°.

Generally, a decrease in sensible heat with a corresponding increase in latent heat and specific humidity is observed from west to east (Figure 6). Although urbanization is expected to result in increased (decreased) sensible heat (latent heat), the resolution of MERRA data is very coarse to attribute any specific change to Dhaka City. The systematic increase of specific humidity along the northeastern direction is indicative of the underlying synoptic condition where monsoonal winds during the months of July–August flow over Bangladesh in the northeaster direction and collide with the mountains in Assam (India).

In order to identify the prevalent wind direction on 28 July 2009 and the historical wind rose diagram, the daily average of eastward and northward wind speed values at 850 hPa were used to determine the direction of wind (Figure 7). For the historical wind rose diagram for July, wind speed data spanning 5 years were used to create the probabilistic map of wind direction and speed using Dhaka city as the center. As expected, historical wind direction and the prevalent wind direction (on 28 July 2009) are found to be in the northeast direction. Using this direction, a group of 10 (eight) rainfall stations was identified as upwind (downwind) of Dhaka city (Table 3). The percentiles (P90, P95, and P99, and the mean) were calculated for the upwind and downwind stations using the 20-year

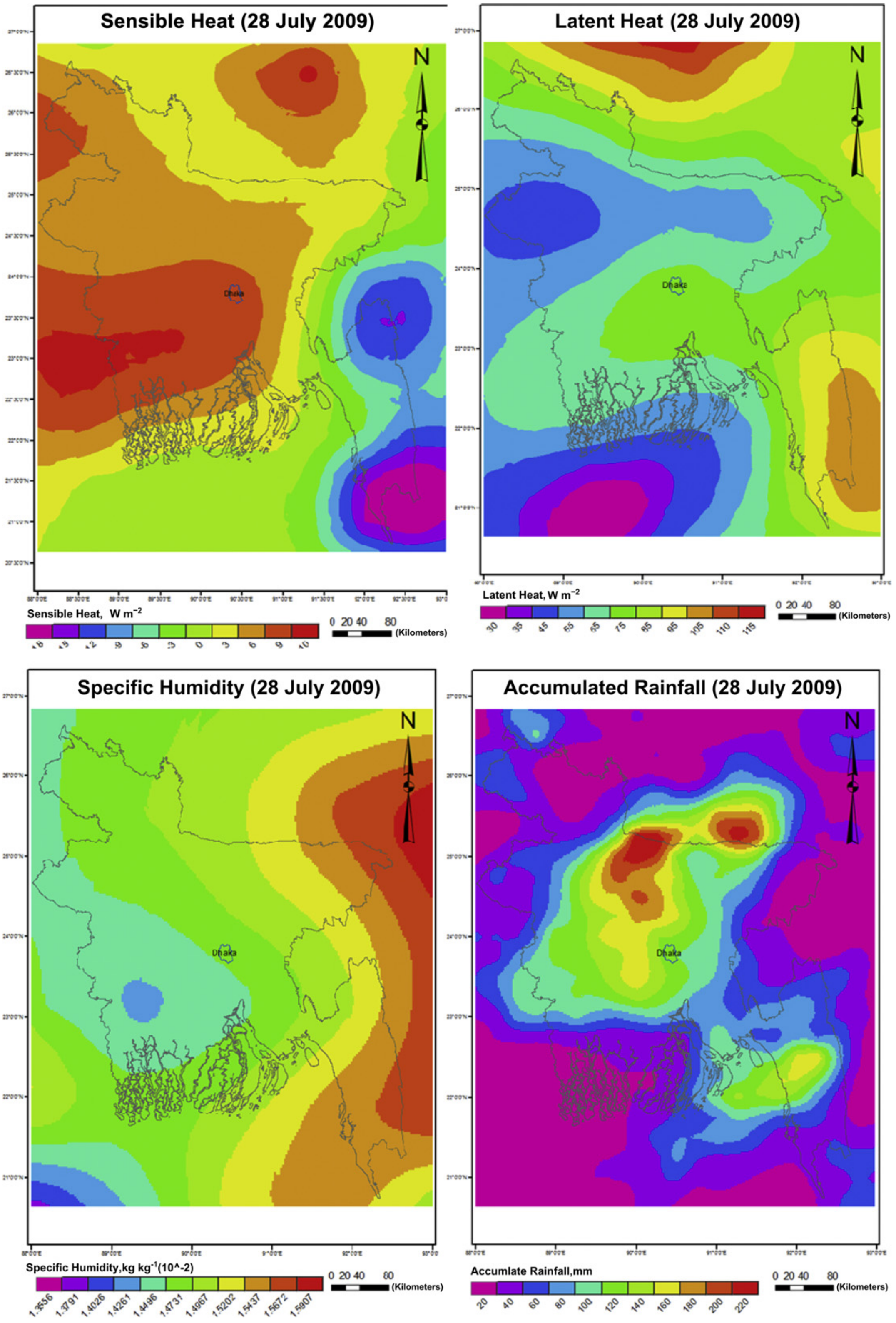
Sensible Heat (28 July 2009)
N
Dhaka
Sensible Heat, W m^{-2}
0 20 40 80 (Kilometers)
Latent Heat (28 July 2009)
N
Dhaka
Latent Heat, W m^{-2}
30 35 45 55 65 75 85 95 105 110 115
0 20 40 80 (Kilometers)
Specific Humidity (28 July 2009)
N
Dhaka
Specific Humidity,kg kg^{-1}(10^-2)
1.3556 1.3791 1.4026 1.4261 1.4496 1.4731 1.4967 1.5202 1.5437 1.5672 1.5907
0 20 40 80 (Kilometers)
Accumulated Rainfall (28 July 2009)
N
Dhaka
Accumlate Rainfall,mm
20 40 60 80 100 120 140 160 180 200 220
0 20 40 80 (Kilometers)

Figure 6 Map of daily averaged sensible heat, latent heat, specific humidity, and accumulated rainfall for 28 July 2009 over Bangladesh.

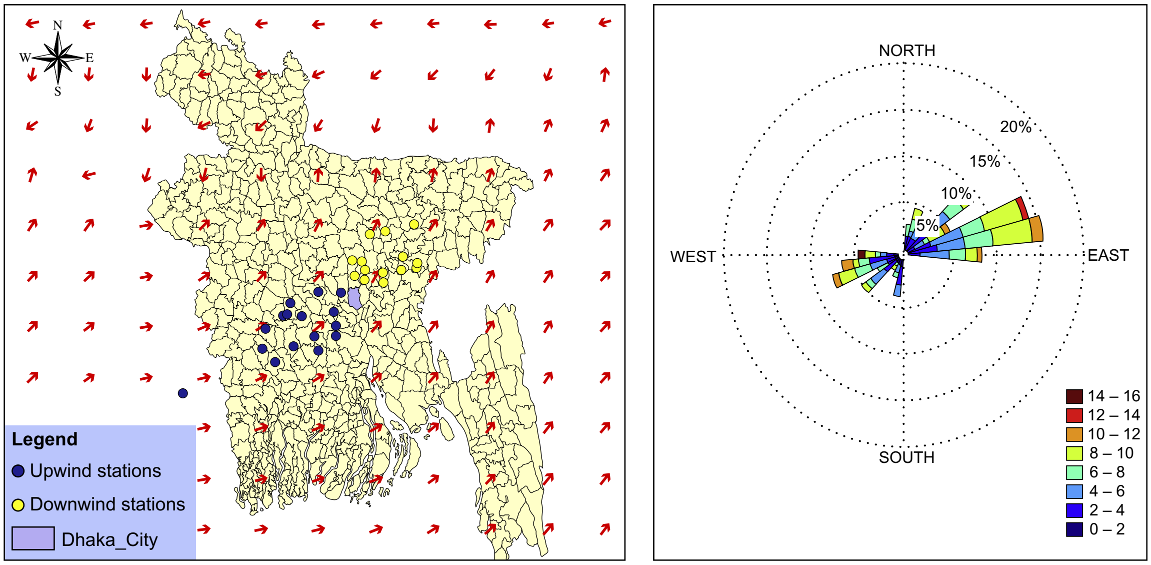

Figure 7 (a) Prevalent wind direction at 850 hPa on 28 July 2009. Blue and yellow colored rainfall stations represent upwind and downwind locations, respectively. (b) July windrose diagram for Dhaka city using 5 years of wind data.

Table 3 Upwind and downwind stations of Dhaka city derived from MERRA wind direction

Upwind station			*Downwind station*		
Station name	*Longitude*	*Latitude*	*Station name*	*Longitude*	*Latitude*
Manikganj	90.0039	23.850	Sreepur	90.5088	24.1475
Rajbari	89.6746	23.7403	Bajitpur	90.9872	24.1940
Baliakadi	89.5934	23.6181	Kishoreganj	90.7782	24.4529
Bhagyakul	90.2128	23.5154	Shibpur	90.7568	24.0365
Bhanga	89.9579	23.4089	Bhairab Bazar	90.9678	24.0694
Fatehpur	90.0039	23.2708	Itna	91.1150	24.5184
Shibchar	90.2157	23.4229	Sarail	91.1463	24.0916
Magura	89.3919	23.4832	Nasirnagar	91.1604	24.1351
Narail	89.5029	23.1573	–	–	–
Salikha	89.3512	23.2870	–	–	–

record of data (Table 4). On an average, it seems the downwind region east of Dhaka city receives about 4 mm more of rainfall a day than its upwind counterpart, which is consistent with historical and contemporary studies (Mote et al. 2007).

Although downwind rainfall is found to be higher for Dhaka city, any physical and direct attribution to urbanization for the 28 July 2009 storm cannot be made given the prevalent condition of a depression in the Bay of Bengal that lasted a few days. For such a land-falling low-pressure system, regions further along the wind direction (such as downwind region east of Dhaka) are naturally expected to experience more rainfall. Lei et al. (2008) studied the catastrophic storm of 26 July 2005 in Mumbai (India) that had similar background synoptic conditions as the 28 July 2009 storm in Dhaka. Using atmospheric modeling, they reported that urbanization potentially contributed to local heavy precipitation at local hotspots and mesoscale precipitation distribution over the Indian monsoon region. Although the urban effect by itself was not found dominant, urbanization appeared to have created conditions that sustained the convergence zone over Mumbai during the duration of the storm.

5.25.4 Assessment of Urban Runoff Generation Potential

In order to understand the ballpark surface water availability from urban runoff generation, a curve number (CN) model was set up to estimate the rainfall partitioning as runoff and recharge/storage. A spatially distributed CN map was first created using high-resolution maps on land use (from LANDSAT) and soils (from Food and Agricultural Organization) at 500 m × 500 m resolution (Figures 8(a) and 8(b)). These two maps were overlaid to derive the CN for each 500 m × 500 m grid box over Dhaka city. There were a total of 1522 grid boxes. A Thiessen polygon map was generated using four rainfall stations near Dhaka city (Figure 8c). The CNs were then lumped as one value (area-weighted composite) for each of the

Table 4 Statistical summary of rainfall percentiles for stations upwind and downwind of Dhaka City in **Table 3** for conditional case (rainfall > 0.0 mm day^{-1})

	Precipitation (mm day^{-1})				
	Mean	*Std. deviation*	*P90*	*P95*	*P99*
Upwind stations	18.93	23.16	40.63	58.92	106.3
Downwind stations	23.58	27.25	51.12	72.25	127.9

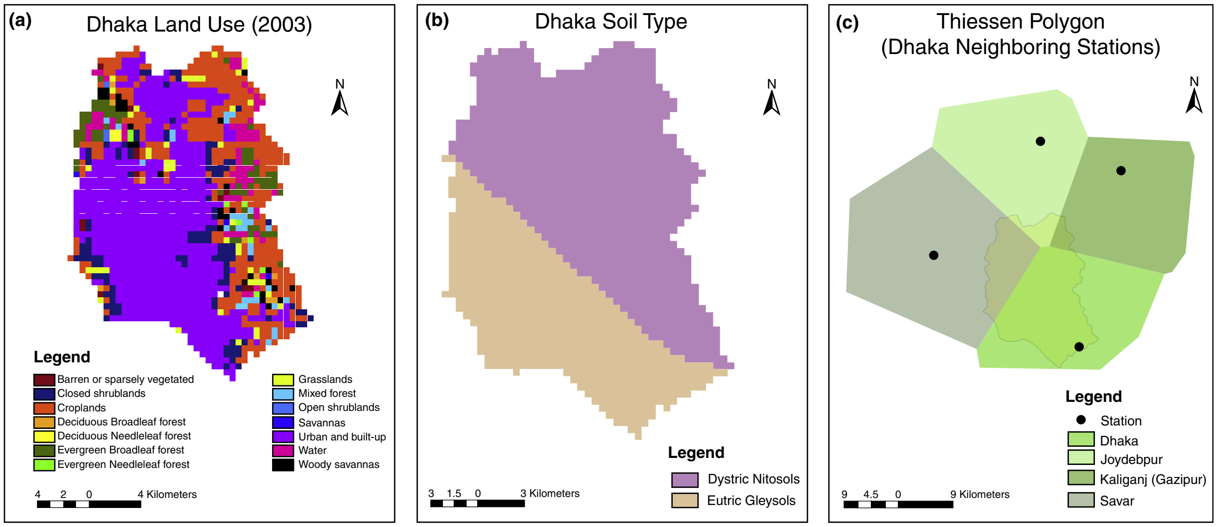
(a) Dhaka Land Use (2003)
N
Legend
Barren or sparsely vegetated
Closed shrublands
Croplands
Deciduous Broadleaf forest
Deciduous Needleleaf forest
Evergreen Broadleaf forest
Evergreen Needleleaf forest
Grasslands
Mixed forest
Open shrublands
Savannas
Urban and built-up
Water
Woody savannas
4 2 0 4 Kilometers
(b) Dhaka Soil Type
N
Legend
Dystric Nitosols
Eutric Gleysols
3 1.5 0 3 Kilometers
(c) Thiessen Polygon (Dhaka Neighboring Stations)
N
Legend
Station
Dhaka
Joydebpur
Kaliganj (Gazipur)
Savar
9 4.5 0 9 Kilometers

Figure 8 Dhaka City land use (a) and soil type (b), and Thiessen polygon for neighboring stations (c).

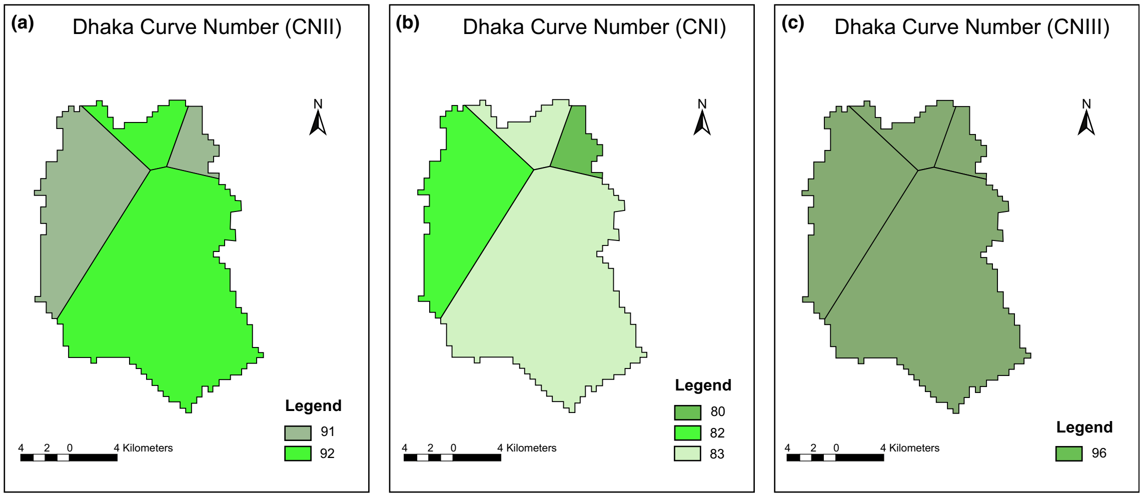
(a) Dhaka Curve Number (CNII)
N
Legend
91
92
4 2 0 4 Kilometers
(b) Dhaka Curve Number (CNI)
N
Legend
80
82
83
4 2 0 4 Kilometers
(c) Dhaka Curve Number (CNIII)
N
Legend
96
4 2 0 4 Kilometers

Figure 9 Dhaka City curve number map for the three antecedent moisture conditions (AMC) – moderate-II (a), dry-I (b), and very wet-III (c). Curve numbers are lumped according to Thiessen polygon representative regions for each station in and near Dhaka City (c).

four Thiessen polygon representative areas of Dhaka city shown in Figure 9. The four rainfall stations were Kaliganj, Dhaka, Savar, and Joydebpur. The preceding 5-day rainfall total was used to determine the antecedent moisture condition (AMC) for each day as I (dry), II (moderately wet), or III (very wet) following the method outlined in Chow et al. (1988) and summarized in Table 5.

The interesting picture that is revealed from this CN-based runoff analysis is that, on an average, about 62% of rainfall usually transforms as runoff and eventually drains into the peripheral rivers of Dhaka as an 'untapped' resource (Table 6(a)). The remaining 38% of rainfall may be considered as a combination of 'recharge,' evaporative losses, and temporary storage. Measurements of groundwater table in Dhaka city

Table 5 AMC classification for curve number model based on preceding 5-day total rainfall

	Total 5-day antecedent rainfall (in.)	
AMC group	*Dormant season (Oct–April)*	*Growing season (Apr–Sep)*
I	<0.5	<1.4
II	0.5–1.1	1.4–2.1
III	>1.1	>2.1

Source: After Chow V. T., D. R. Maidment, L. W. Mays, 1988: *Applied Hydrology*. McGraw-Hill International Editions, Civil Engineering Series.

indicate that the table is declining at the rate of 2–3 m year^{-1}, indicating that the uptake is not sustainable in comparison to natural recharge rates (Rahman and Hossain 2008). On the other hand, for a heavy storm, such as on 28 July 2009, more than 95% of the rainfall transforms as surface runoff and eventually drains into rivers and water bodies (Table 6(b)). If the rainfall and the urban runoff from moderate-to-heavy storms could be harvested, it could provide Dhaka with an alternate supply of water to relieve the pressure on its dwindling and renewable water resources.

5.25.5 Discussion

What could be the strategy for future water resources planning based on the above vulnerability assessment in the context of rapid urbanization? There are two key findings that can be used to promote sustainable use of water resources for a megacity such as Dhaka. First, rainfall has a spatial gradient where the downwind region seems to receive statistically higher rainfall than the upwind region. Although such a spatial pattern cannot yet be physically attributed to rapid urbanization, the observation itself has merit for policy planners. Second, urban regions around Bangladesh in general receive less rainfall than the nonurban regions. At the current state of urbanization for Dhaka city, approximately 62% of the rainfall is available as urban runoff, which currently is untapped as a potential mitigating source.

Such a preliminary assessment of urban runoff points to the feasibility of a Seletar-Bedok-type urban runoff harvesting reservoir as in Singapore for supplementing the traditional aquifer-based water supply. At the current growth rate, water demand for Dhaka city is expected to reach 3.2 million m^3 per day (Mm^3/day), or 3200 million l day^{-1}, by 2025 (Figure 10). According to the CN-based runoff assessment shown in Table 5, the long-term daily runoff generation potential for Dhaka city is around 3.06 Mm^3 day^{-1}. Assuming a 50% urban runoff capture efficiency for a runoff harvesting reservoir, about 0.7 Mm^3 day^{-1} of this urban runoff may be used for artificial recharge to systematically raise the groundwater table. The remaining 0.8 Mm^3 day^{-1} amount could be treated for suspended solids removal and then used for nondrinking consumption. Such a conjunctive approach would not only relieve pressure on the deep aquifers, but also gradually counter the declining groundwater table and build strategic storage for use later in the century. For the heavy storms, more than 90% of the rainfall is generated as runoff. This indicates that rainwater harvesting should be promoted in the downwind regions located east of Dhaka city and transported back for urban consumption as drinking water through bottling or a network of pumping stations and pipe networks.

A recent pilot-scale study implemented by the Bangladesh Institute of Water Modeling (IWM) for Dhaka Water Supply and Sewerage Authority (DWSSA) during 2011 indicated that rainfall and runoff harvesting can indeed be successful in cost-effective recharge of ground water by using injection well by gravity (IWM 2011). In fact, this pilot-scale study demonstrated that if *60% of the total rainfall from concrete roof tops of the city area can be harvested then annually about 89,496 millions of liters rain water will be available for artificial recharge to aquifer…can make*

Table 6a Long-term 10-year water balance for Dhaka City (1986–1995)

CN region based on Thiessen polygon rainfall station	*Representative area (km^2)*	*Total rainfall volume (Mm^3)*	*Total runoff volume (Mm^3)*	*Total storage volume (Mm^3)*
Kaliganj (Gazipur)–Joydebpur	16.69	548	286	262
Joydebpur	24.75	814	425	388
Savar	96.00	4487	2745	1741
Dhaka	243.06	12,184	7712	4472
Total	380.50	18,035 (100%)	11,170 (62%)	6864 (38%)

Mm^3, million cubic meter.

Table 6b Water balance for Dhaka city on 28 July 2009

CN region based on Thiessen polygon station	*Representative area (km^2)*	*Rainfall volume (Mm^3)*	*Runoff volume (Mm^3)*	*Storage volume (Mm^3)*
Kaliganj (Gazipur)–Joydebpur	16.69	4.61	4.41	0.21
Joydebpur	24.75	6.84	6.54	0.30
Savar	96.00	10.08	8.96	1.12
Dhaka	243.06	108.89	105.86	3.03
Total	380.50	130.43 (100%)	125.77 (96%)	4.66 (4%)

Mm^3, million cubic meter.

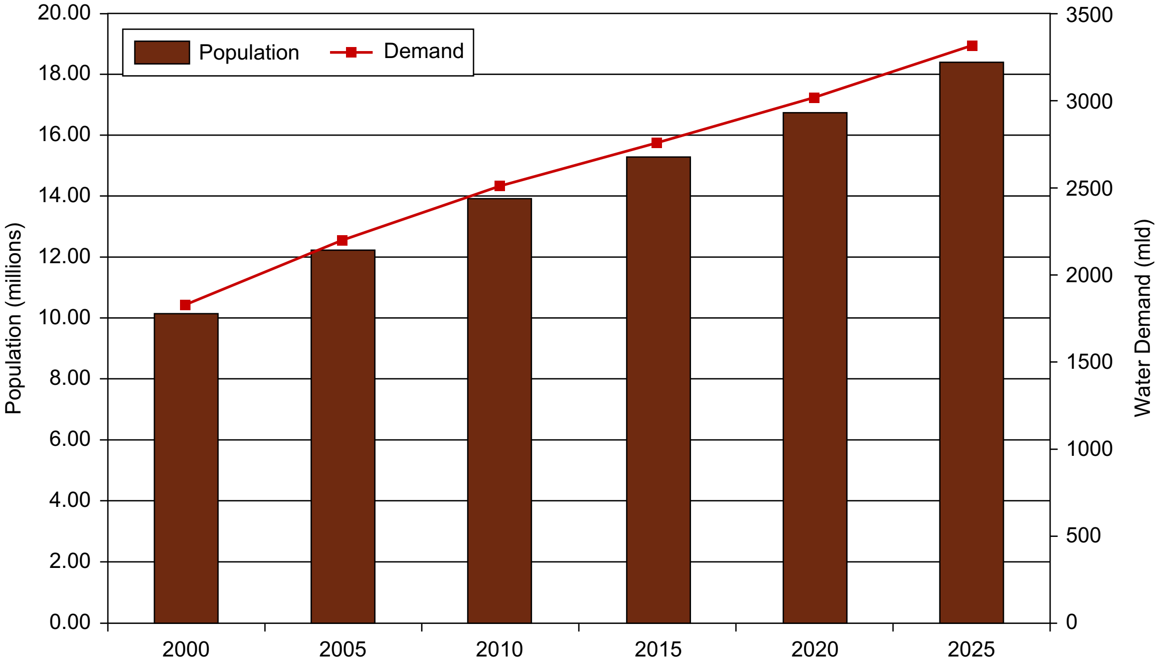

Figure 10 Population and water demand projection for Dhaka city. Unit for water demand is million liters per day (mld). Source: After Rahman, S. and F. Hossain, 2008: Spatial assessment of water quality of peripheral rivers of Dhaka City for optimal relocation of water intake point. *Water Resour. Manag.*, **22** (3), 377–391, http://dx.doi.org/10.1007/s11269-007-9167-y.

245 million liters per day for city water supply. Such an endorsement of our vulnerability assessment approach through an independent pilot-scale study (i.e., earlier we claimed in our study that about 62% of rainfall is potentially an untapped resource for Dhaka) demonstrates the effectiveness of the bottom-up approach as a decision-making tool for the adaptation community. Overall, this study demonstrates that an accurate understanding of the rainfall and runoff modification patterns in the context of rapid land use change (such as urbanization) using a bottom-up assessment approach is critical to forecasting future water resources vulnerability and for designing harvesting schemes.

5.25.6 Conclusion

This study explored the water resources vulnerability for Dhaka city in the context of rapid land use change that compromises the sustainability of its renewable water resources. Using observational evidence, it found that rainfall experienced strong spatial signature, where the region downwind of the city seemed to receive statistically higher rainfall than the upwind region. Direct physical attribution to rapid urbanization of Dhaka city was not possible for the 28 July 2009 storm that broke a 53-year record. In the wider context of the country, the study also found that urban regions in general receive less rainfall than the nonurban regions.

As a future extension of this study to pinpoint more specifically the plan for sustainable water resources development, atmospheric modeling combined with investigation of local convective initiation should be carried out. Such a study would help policy planners understand if future urbanization may alter the frequency and intensity of heavy rainfall events in the context of a changing climate. The CN model used for urban runoff in this study provides only an external description of water availability (e.g., Dhaka city as the control volume). More sophisticated models for urban runoff such as Storm Water Management Model (SWMM) or MIKE-URBAN could be used for detailed planning in the near future. Such models take into account the topography and urban drainage network consisting of pipes and open channels and, provide, as a decision-making output, optimal locations for capture of runoff. Such modeled locations can be potential feasibility sites for the Selatar-Bedok-type urban runoff capturing reservoir or for artificial recharge of groundwater. Although this study shows promise for a sustainable water resources development plan for Dhaka city, it is only with such detailed models and further analysis that the design specifications of systems be identified to safeguard the water security of South Asian megacities such as Dhaka.

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The index is arranged in set-out style with a maximum of three levels of heading. Major discussion of a subject is indicated by bold page numbers. Page numbers suffixed by t and f refer to tables and figures respectively. vs. indicates a comparison.

This index is in letter-by-letter order, whereby hyphens and spaces within index headings are ignored in the alphabetization. For example, 'databases' is alphabetized before 'data collection'. Prefixes and terms in parentheses are excluded from the initial alphabetization.

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